Studies into the effectiveness of starter band applied phosphorus to Russet Burbank potatoes grown on ferrosol soils in Tasmania.

by

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Abstract

A large proportion of Tasmanian and Victorian potatoes are grown on ferrosols, which have the highest Phosphorus (P) fixing capacities of any agricultural soils in Australia. Phosphorus rates well in excess of maintenance dressings are commonly used on potato crops grown on ferrosols. This is an increasing economic cost to growers and a cost to soil and potato quality because of the significant addition to soil P and cadmium (Cd) loads. Starter fertilisers have proved successful at improving the initial P nutrition and subsequent fertiliser efficiency of crops but have not been extensively trialed with potatoes.

Field trials investigating the use of starter fertilisers on cv. Russet Burbank potatoes were conducted over three years on ferrosol soils on the North West Coast of Tasmania. Granular starter bands were used in the first year and liquid starter treatments were applied in the second year. In the final year granular starter bands in combination with hill-placed dripper and standard sprinkler irrigation were trialed. The distribution of potato roots was measured and correlated with soil strength and moisture properties and the fate of irrigation water applied to the potato canopy was studied on field grown plants and by a computer model. The effects of P rate and irrigation method on ground cover development were also measured. Glasshouse and laboratory trials were conducted to investigate the effects of starter fertiliser treatments and soil conditions on plant and root growth.

No starter phosphorus application improved final tuber yield. Initial petiole weight and nutrient responses were found in the first year to starter P application and from drip irrigation of conventionally banded P, but not from the starter P band. Liquid starter P improved the P nutrition of glasshouse grown plants but had no effect on early plant nutrition or final tuber yield of field grown potatoes. Subsequent glasshouse experiments indicated that higher strength liquid solutions could be used without long term injury to potato plants. Ground cover development was hastened by P applications of 100 kg P ha^{-1} or more and by drip irrigation in the absence of applied P. Total tuber yield was moderately correlated to ground cover measurements and there were indications that higher P applications improved the utilisation of solar radiation.

There was evidence of root proliferation in the region of conventionally banded fertilisers but no indications of proliferation in the region where starter fertilisers were applied. When potato plants were left unhilled roots were able to grow out to and beyond the perimeter of the canopy. There was a prominent absence of root growth in the wheel-compacted soil of both unhilled and hilled potatoes with only sparse root growth into soil regions with bulk densities of 1.05 Mg m^{-3} and greater. Penetration resistance of soils with bulk density > 1.1 Mg m^{-3} increases sharply with drying to reach strengths capable of restricting root growth. Soils of lower bulk density are unable to reach penetration resistances that could inhibit potato root growth at any moisture content.

Up to 20% of the water applied to the potato canopy can be displaced laterally to the furrows giving rise to an increased water application of the furrows and a corresponding decrease in water application to the hill soil. The combined effects of water shedding from the canopy, a reduction of lateral root growth from the hilling of potatoes, and furrow compaction, have implications for irrigation efficiency and phosphorus uptake of potato crops.

Potatoes were able to grow a large root system before nutrients from the sett were exhausted. Conventionally banded fertiliser at 50 mm beside and 50 mm below the sett appeared to be sufficiently close to supply P before yield-limiting P deficiency occurs. Poor root contact or unfavourable soil moisture regimes may inhibit the acquisition of nutrients from fertilisers placed with or above the sett.

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1.1 Introduction

Potatoes for processing are amongst the highest value crops grown in Tasmania (Matherson, 1999) and a major crop in Victoria. A large proportion of Tasmanian and Victorian potatoes are grown on krasnozems (hereafter referred to as ferrosols, Isbell 1996). Smaller areas are also grown on ferrosols in the Atherton Tableland in Queensland, and the Robertson and Dorrigo areas of NSW (Cotching, 1995). Ferrosols are therefore important soils for Australian potato production.

Ferrosols are highly weathered soils developed on basic igneous rocks and contain a high proportion of finely divided iron and aluminium oxides. These minerals are responsible for the excellent structure of ferrosols, but they are also responsible for "fixing" phosphorus (Moody 1994). Ferrosols have the highest P fixing capacities of any agricultural soils in Australia (Burkitt *et al.,* 2001). On these soils, P must be banded for good yields; without banding, P fixation is accentuated. However, even with banding, rates of P needed for optimum yield and quality are often 150-250 kg P ha^{-1} (Sparrow *et al.,* 1992). Low soil temperatures at planting may be partly responsible for the high P needs of potatoes on ferrosols in cooler areas like Tasmania and Victoria, since the rate of P uptake (Barber, 1980) and organic matter mineralisation (Black, 1957) are reduced by cooler temperatures. The high P rates are a cost to growers which has increased recently, and a cost to soil and potato quality because they add significantly to the soil P and cadmium (Cd) load.

For potatoes on ferrosols, P is usually banded in two strips on either side of and about 50 mm below the seed sett. However, in spite of the increased P efficiency which banding affords, total crop P uptake is at most about 40 kg P ha^{-1} for a 60 t ha^{-1} crop and only a small proportion of this comes from the fertiliser. For example, Pursglove and Sanders (1981), using isotopically labelled P fertiliser, found that only 4% of the fertiliser P was recovered by the crop. Clearly there is scope to improve the efficiency with which P fertiliser is used, and closer than normal banding of P fertiliser at planting would seem a possible strategy. Despite this scope, there has

been no work in Australia to look at improving P fertiliser efficiency in potatoes through close placement.

The effect of P fertiliser placement on its recovery by plants is considered to be the net effect of competing mechanisms (Holford 1989). On the one hand, concentrating the fertiliser in a smaller volume of soil decreases soil-fertiliser contact and thus minimises fixation. It also stimulates root growth in the band (Duncan and Ohlrogge 1958). On the other hand, excessive fertiliser concentration in bands can cause P to precipitate. A simulation model of P uptake constructed by Kovar and Barber (1989) showed that the optimum volume of soil to fertilise with P decreased as the P buffer power of the soil increased. Ferrosols have a high P buffer power (Moody 1994).

There have been many studies on close placement of fertiliser (Laughlin 1968; Bermudez and Mallarino 2002), but few on potatoes have been reported. Much work has been done on P coating of pasture seeds to help establishment, mostly glasshouse trials. This work has shown that effects of P seed coating are often most pronounced early in growth, and that the most soluble P sources, including commercial superphosphates, can actually inhibit growth because they form acidic solutions upon dissolution. The effect of acidity can be overcome by mixing such P sources with lime. Combining ammonium nitrogen (N) with P can boost the P benefit (Duncan and Ohlrogge, 1958). The ammonium is thought to stimulate P uptake e.g. (Sanchez *et al.,* 1989; Rebafka *et al.,* 1993) and may also decrease the amount of soil aluminium dissolved by the fertiliser because ammonium phosphates dissolve to give a more alkaline solution than superphosphates (Russell 1973; Moody *et al.,* 1995b). The latter could be important in ferrosols.

Tindall *et al.* (1993) report that in Idaho, USA, starter NP bands are placed above the seed in addition to conventional bands below and to the side of the seed. In Idaho, the close bands are applied at rates of about 20 kg ha^{-1} of both N and P. There the soils are alkaline, and mono-ammonium phosphate is used to avoid generation of ammonia gas, which is toxic to the germinating seed. While ferrosols are not alkaline, and di-ammonium phosphate could safely be used on such soils, there is a greater risk of salt induced calcium deficiency (Moody *et al.,* 1995a) with di-ammonium than mono-ammonium phosphate.

Pilot studies in Tasmania in both the field and glasshouse (Sparrow unpublished data) have suggested that seed coating is sometimes detrimental to potatoes, but that close placement within 1 cm of the seed is not. For this reason, and because of the probable difficulty of developing a practical system for coating potato seed with fertiliser, this work has focused on close placement.

The placement of some of the fertiliser with or above the potato sett has been shown to improve the yield of potatoes by locating the fertiliser in the region with the highest root density (Kleinschmidt, 1983). However, some mixing of the starter fertiliser through the surrounding soil may be desirable since the growth of young roots is limited and they may not encounter fertiliser if it has been confined to a narrow band (Costigan, 1987). Alternatively, soaking the seed tubers in low strength P solutions (Sharma and Gerwal, 1989) can reduce the P requirement of potatoes. The phosphorus solutions are absorbed into the interstitial spaces from where they can be absorbed into the cells. Liquids applied into the soil directly over the sett at planting tend to dissipate into the soil around the outside of the seed where early root grow occurs. Liquid starter solutions may provide methods both for the placement of starter fertiliser and to allow the potential for uptake of P even before the roots develop.

Since phosphorus moves to roots primarily by diffusion, soil moisture directly affects the uptake of P from soil P reserves and fertiliser P sources (Jungk and Claassen, 1997). Higher rates of irrigation can improve the recovery of banded and broadcast P fertilisers (Baerug and Steenberg, 1971). The effects of irrigation on P efficiency from starter bands have not been investigated.

The canopies of a range of crops have been shown to interact with overhead irrigation and rainfall (Xiao *et al.*, 2000; Carter *et al.*, 2000; Ellsbury *et al.*, 1996). In potatoes, Saffigna *et al.* (1976) observed preferential flow of overhead irrigation water down the stems and to the outer edge of the canopy. The potato canopy can redirect overhead irrigation water away from the hilled soil and into the furrows. When applying irrigation water to crops through furrow irrigation the water tends to move to the base of the hills and then upward due to root absorption of the water in

the hill (Taylor and Ashcroft, 1972; Noborio *et al.*, 1996). The upwards movement of water through the base of the hill could favour P uptake from the conventionally banded position while the drier conditions in the hill would retard P uptake from the starter position.

Irrigation water can be applied directly to the hill soil through drip irrigation which may enhance the uptake of both starter and conventional band placed P and potentially increase the uptake of P retained in the soil. In addition, drip irrigation increases the water use efficiency and enables better scheduling of irrigation (Shock *et al.*, 1999). Since potato yield is increased in direct proportion to reductions in average soil moisture tension (Taylor and Ashcroft, 1972), more frequent applications of water through drip irrigation can lower the average moisture tension and thereby increase yield and P uptake.

This thesis reports on field experiments which were conducted in three consecutive growing seasons. The first experiment was designed to test the benefit of a granular starter fertiliser placed above the seed as reported by Kleinschmidt (1983). In the second year's trial the starter P was applied as a low strength liquid solution directly over the sett. Excavations of young plants during the first year's trial had revealed substantial root growth around and below the sett, but only limited growth in the soil above the sett. Laboratory experiments had indicated that dilute P solutions could improve the early growth of potato shoots. In the final field trial the effects of dripper and sprinkler irrigation on granular starter band treatments were compared. While the liquid treatments of the second trial had had no effect, there were indications that potato growth was strongly affected by variations in irrigation. A more favourable moisture regime in the hill soil, through drip irrigation, may promote better utilisation of fertiliser and soil P reserves.

1.2 Fertiliser placement for potatoes

Three methods of fertiliser placement are commonly used on potatoes; broadcast, banded and starter fertilisers (Beukma and VanDerZaag, 1990). Broadcast fertilisers are mixed thoroughly with all or a significant proportion of the rooting depth soil volume. Banded fertilisers are confined to single or double fertiliser strips. These have a smaller surface in contact with the soil and consequently less fertiliser is inactivated through soil fixation (Barber, 1995). Starter fertilisers are a specific variation on band and broadcast placement where a small quantity of fertiliser is placed close to the seed to promote early growth (Costigan, 1984). In most circumstances, the full rate of fertiliser required for the crop when close placed would cause fertiliser injury (Chu *et al.,* 1984).

Traditionally, fertiliser application has been by broadcasting. This is the simplest form of fertiliser application and is still practised on potatoes grown in Tasmania, though rarely for crops grown on ferrosols (Sparrow *et al.,* 1992). However, only 2% of the soil volume in the root layer may be supplied with phosphorus by broadcast fertiliser (Engelstad and Terman, 1980). Young plants may have difficulty acquiring enough fertiliser during early growth due to their small root systems (Costigan, 1987) which can contribute to initial P deficiency and reduced yield. Banded phosphorus fertiliser has proved to be more efficient then broadcast P on ferrosols (Sparrow *et al.,* 1992).

1.2.1 Banded fertiliser

Banding phosphorus fertiliser usually improves the phosphorus efficiency of crops (Barber 1995). Only when soils have a very low P fixing capacity does broadcast fertiliser match or improve the fertiliser efficiency (Hegney and McPharlin 1999). The most efficient position for banded fertiliser depends on several crop factors. Crops most likely to benefit from band placement of fertiliser are those that have limited initial root growth, a short growing season or are susceptible to fertiliser injury when fertilisers are placed with the seed Laughlin (1960). Crop row spacing may also influence the response to banding, since at a given fertiliser application as the row spacing is decreased so too is the quantity of fertiliser in each band. Plants that develop a tap roots are most likely to benefit from fertiliser banded directly

below the seed, while banding beside and below the seed is more effective for crops with fibrous roots Laughlin (1968). Potatoes grown from seed tubers develop a fibrous root system (Cutter, 1978).

A summary of yield responses of potatoes to various banding locations is show in Table 1-1. Placing the fertiliser on the same level or slightly below and beside the seed gives the highest yields. There is a very high response from the deep banding of fertilisers 150 mm below the seed (Holliday and Draycott, 1968). This position was more effective during dry years due to the greater moisture reserves in deeper soil but the benefit may be reduced with higher rates of irrigation. Placing fertiliser above or directly below the seed reduces yield.

Table 1-1. Relative yield responses of various fertiliser placements compared to placement at 50 mm beside and 50 mm below the sett.

	Lateral distance from seed (mm)			
Depth (mm) from seed	0	25	50	75
75	-	-	-	0.86 (c)
50	0.95 (c f)	-	-	-
25	1.00 (f)	-	-	-
0	0.93 (c)	1.03 (c)	1.10 (c)	0.98 (c)
-25	0.94 (c)	-	0.96 (g)	-
-50	0.94 (c,b)	-	1.00 (g)	-
-75	0.90 (e)	-	1.00 (a)	0.80 (e)
-150	-	-	1.26 (d)	-

Data compiled from experiments comparing two or more banding positions with at least one at 50 mm beside and 50 mm below sett (; a, Campbell *et al.*, 1945; b, Cooke, 1948; c, Cumings and Houghland, 1939; d, Holliday and Draycott, 1968; e, Soltanpour, 1969; f, Widdowson *et al.*, 1974; g, McEwen and Johnston, 1979)

Jacob *et al.* (1949) found total phosphorus fertiliser uptake for potatoes was lower than other crops including corn, soybean, and cotton, because the root system of potatoes was smaller. Pursglove and Sanders (1981) supposed the low root density of potatoes was likely to hinder further improvements in phosphorus recovery. Prumel (1957) believed phosphorus banding in potatoes was less effective because

roots quickly extend beyond banded regions into the bulk soil. Substantial amounts of soil phosphorus can then be removed from the bulk soil (Prumel, 1957).

Yost *et al.* (1979), working with corn grown in ferrosol, found initial broadcast phosphorus applications followed by lighter band applications in subsequent years could improve the efficiency of phosphorus fertiliser. Aitken and Hughes (1980) found banding only significantly improved yield compared to broadcast fertilisers at low rates of phosphorus application. This result was also found by Fox and Kang (1978) for corn. Kamprath (1967) and Holford (1989) found complete mixing to be advantageous as this distributed phosphorus throughout the soil volume and maximised the potential root interception of P. However, soil properties have a large influence on the likely response to banding, hence on light textured soils with low P fixing properties, favourable responses to broadcast P are often found (Hegney and McPharlin, 1999). On high P fixing soils banding was more efficient (Sparrow *et al.*, 1992).

Barber (1995) found phosphorus utilisation was greatest when phosphorus was mixed with around 5-15% of the soil volume, depending on the phosphorus fixing capacity of the soil. Soils with high phosphorus fixing capacities reached their optimum fertilised ratio at lower P mixing volumes. This is the optimum condition between allowing root access to the confined phosphorus in the band and preventing loss of phosphorus to fixation when phosphorus is mixed with larger soil volumes. When the phosphorus fixing capacity of the soil increases, the volume of fertilised soil should be decreased (Barber, 1995). However, even on high phosphorus fixing soils restrictions on the fertilised soil volume below 5% can be limited by inefficiencies from reduced root contact with the fertiliser.

The Tasmanian recommendations for fertilising potatoes are to band fertiliser 50 mm below and 50 mm beside the sett on each side (Anon., 1969; Regel, 1988; Myuller, 1991). Closer placement of banded fertiliser may result in fertiliser injury (Regel & Sampson, 1987). Banding with the sett has been successful only when low rates of fertilisers were used (Prumel, 1957). Placing the fertiliser bands deeper in the soil, where moisture is more likely to persist, improved the P uptake of potatoes in drier treatments but was no more effective than conventional band placement in well

irrigated potatoes (Holliday and Draycott, 1968). Even when high levels of soil moisture are maintained, there is still a greater response to banded than broadcast fertilisers (Baerug and Steenberg, 1971).

1.2.2 Starter fertiliser

The term "starter fertiliser" is used to describe a variety of banded fertiliser treatments. Starter fertilisers here are defined as a small proportion of the total fertiliser placed closer to the seed than is the bulk of applied fertiliser (Bednarz *et al.*, 2000; Swiader and Shoemaker, 1998). The main fertiliser application may be either broadcast or banded. Starter fertiliser is intended to improve the early nutrition and hence vigour of the crop (Engelstad and Terman, 1980) which may or may not beneficially affect the final yield (Robertson *et al.*, 1954).

Crops often require higher phosphorus concentrations during early growth (Scott, 1988) and close placement of immobile nutrients, such as P, is important, especially under cool conditions when phosphorus uptake is reduced (Klepper *et al.*, 1983). Starter fertilisers have proved advantageous where early root growth is restricted (Costigan, 1987), Al toxicity occurs (Sloan *et al.*, 1997) or soil temperatures are low (Robson *et al.*, 1959). These responses were due more to the positioning of P rather than the absolute rate of applied P. Basal and top-dress fertiliser applications can be reduced by the use of starter fertilisers (Stone, 2000).

1.2.3 The chemical environment around fertilisers

Fertilisers are usually required to obtain maximum crop yield. However, the ionic environment in the immediate vicinity of the fertiliser band can restrict or prevent root growth. Nutrients in the fertiliser band may be in a chemically "available" form, as measured by soil nutrient analysis, but biologically inaccessible to the plant due to a toxic or inhibitory ionic environment (Blanchar and Caldwell, 1966b; Moody *et al.*, 1995b).

Fertiliser efficiency is dependent on the interaction between plant roots and the form and distribution of nutrients in the soil. The addition of fertilisers affects a suite of soil attributes, some of which can impair a root's ability to grow or acquire nutrients, even if only in localised regions around the fertiliser. Root growth in the immediate

vicinity of fertilisers may be restricted by toxicities such as aluminium (Bruce *et al.*, 1988), manganese (White *et al.*, 1970) and ammonia (Bennett and Adams, 1970b; Moody *et al.*, 1995a) and deficiencies of calcium (Bennett and Adams, 1970a; Moody *et al.*, 1995b). Salinity also inhibits root growth, particularly if nitrate and chloride based fertilisers are used (Moody *et al.*, 1995a). Plant cadmium uptake can be increased by the rate of band applied P (Sparrow *et al.*, 1992) and by other fertiliser ions, particularly chloride, (Sparrow and Salardini, 1997). To maximise fertiliser efficiency, nutrients must be in a position and chemical environment where they are at their highest availability to the root system. It is important to understand the development and physiological responses of roots growing into fertilised soil in order to optimise the utilisation of applied fertilisers.

The close placement of fertilisers may cause injury to seedlings by a range of salinity and specific ion effects. Soil solution concentrations may be substantially increased around fertiliser bands (Lindsay and Stephenson, 1959a). Mono-calcium phosphate (MCP), super phosphate and mono-ammonium phosphate (MAP) reduce the pH in the vicinity of fertilisers, while di-ammonium phosphate (DAP) increases the pH (Huffman and Taylor, 1963). The dissolution of soil minerals under strongly acidic conditions releases substantial amounts of Al^{3+}, Fe^{3+}, Si^{4+} and Mn^{2+} into solution (Lindsay and Stephenson, 1959a; Moody *et al.*, 1995b). This may cause both Al^{3+} and Mn^{2+} toxicities and possible H^{+} toxicity when the pH is very low. Lindsay and Stephenson (1959a) found Mn^{2+}, released from around MCP bands, remained in solution longer than Fe^{3+} and Al^{3+} and was able to diffuse further into the soil than Fe^{3+} or Al^{3+}. This was due to the greater solubility of Mn^{2+} at the higher pHs found further from the band, Mn^{2+} is stable up to pH of 6 (Bohn *et al.*, 1979) and the lack of precipitation reactions between Mn^{2+} and phosphorus (Lindsay and Stephenson, 1959a).

1.2.3.1 Aluminium

Aluminium affects root growth through the inhibition of nutrient uptake, particularly phosphorus, and by interfering with cell division (Marschner, 1986). The Al^{3+} ion may precipitate with phosphate either in the intra cellular root-free space or in close association with the nucleus. The accumulation of alumino-phosphates within the root-free space is caused from precipitation of soluble alumino-phosphates within the

root and by the adsorption of phosphate to previously precipitated Al hydroxy polymers (Marschner, 1986). Such phosphorus is not readily available for plant uptake. The binding of Al^{3+} to the phosphate groups of DNA increases the stability of DNA and prevents strand separation, essential for replication. Hence, Al^{3+} bound to DNA inhibits cell division. Potatoes are relatively tolerant to Al toxicity (Hooker, 1981), though Horst and Schmohl (2001) demonstrated relative root elongation rates of 55% occur at 25 ¼mol Al^{3+} for several potato varieties. Aluminium toxicity only becomes a problem when strongly acidifying fertilisers are used. The effect is moderated by the strong affinity of phosphate for aluminium (Lindsay and Stephenson, 1959b). Strongly acidic fertilisers should be avoided for use in starter bands.

1.2.3.2 Manganese

Potatoes are somewhat more sensitive to manganese than aluminium toxicity (White *et al.*, 1970), with growth being reduced by concentrations of 25 ppm Mn^{2+} in solution cultures (Hooker, 1981). The shoot tissue of plants is more susceptible to Mn toxicity than root tissue (Brown and Devine, 1980; Horst, 1988). Plants can tolerate small zones of elevated Mn, so long as the total Mn supply to the shoots remains below the toxic threshold (White *et al.*, 1970). However, very high Mn^{2+} concentrations may cause root damage, (Wong and Bradshaw, 1982 cited in Horst, 1988).

Long term exposure to Mn is more damaging to root growth than short-term exposures. Mn levels as low as 8.5 ¼mol may damage roots after long term exposure (Wong and Bradshaw, 1982 cited in Horst, 1988). This value is ten fold lower than the Mn level for a 10% reduction in relative root elongation during short-term exposure found by Moody *et al.* (1995c).

1.2.3.3 Ammonia

Ammonium ions can contribute to toxic concentrations of ammonia at high concentrations (Ouyang *et al.*, 1998). This effect is moderated by the soil pH, with higher pHs giving rise to elevated and toxic ammonia concentrations (Bennett and Adams, 1970b; Moody *et al.*, 1995b). Ammonium is fixed less strongly by soil than is phosphate (Gerendas *et al.*, 1997) and can diffuse further from fertiliser bands (Blanchar and Caldwell, 1966a). Ammonia toxicity is more likely to occur in soils

with low cation exchange capacity (CEC) that are unable to buffer the increase in ammonium concentration (Chu *et al.,* 1984) and changes in pH. Ferrosols, with their moderate CEC, are less likely to permit ammonium concentrations to develop to toxic levels (MacLean, 1983; Moody *et al.,* 1995b) except at distances very close to the fertiliser band. The vaporisation of ammonia is reduced at lower pH (Findenegg, 1987), hence ammonia activity from an acidifying fertiliser like MAP is less likely to reach levels that are toxic than is DAP which gives an alkaline reaction. Phosphorus uptake is improved by the inclusion of some N in the ammonium form compared to nitrate N (Duncan and Ohlrogge, 1958; Miller and Ohlrogge, 1958; Hoffmann *et al.,* 1994). There are advantages to the inclusion of some ammonium N in starter fertiliser bands.

1.2.3.4 Calcium deficiency

Calcium is essential for cell growth, and is used for cell wall formation and cellular regulation (Marschner, 1986; Poovaiah and Reddy, 1991). Calcium has a stimulatory effect on phosphorus uptake but only at low solution phosphorus levels (Robson *et al.,* 1970). Calcium promotes the initiation of lateral roots, at concentrations as low as 0.1 mmol. Magnesium functions in a similar way to calcium by stimulating phosphorus uptake and being involved in cellular regulation but magnesium cannot be used for cell wall synthesis and so cannot completely replace calcium (Adams, 1980).

Most soils supply enough Ca for adequate growth but Ca concentrations may be reduced to deficient levels when the activity of another cation is increased, e.g. NH_4^+ (Moody, 1995b), when Ca is lost by precipitation with phosphate (Naidu *et al.,* 1990), or when Ca deficiency is induced at high phosphorus concentrations due to the simultaneous uptake of Ca and phosphorus ion pairs (Robson *et al.,* 1970). Calcium is prevented from moving across cell membranes (Greenwood and Collier, 1979) hence very little Ca enters the phloem from the xylem. Any Ca that does enter the phloem is rapidly precipitated with phosphate. Calcium must be present at the growing root tip since very little redistribution of Ca occurs (Greenwood and Collier, 1979).

The response of plants to soil calcium status shows a better correlation with calcium activity ratio (CAR) than the absolute Ca concentration in the soil solution (Blanchar and Caldwell, 1966b; Khasawneh, 1971; Bruce *et al.*, 1988; Moody *et al.*, 1995b). CAR is defined as the Ca activity divided by the sum of all cation activities. $CAR = [Ca]/\Sigma([Ca^{2+}]+[Mg^{2+}]+[K^{+}]+[Na^{+}]+[Al^{3+}]+[NH_4^{+}]+[Fe^{3+}]+[cation^{+}]...)$. The typical CAR for adequate root growth of soybeans ranges from 0.05 (Moody *et al.*, 1995a) to 0.15 (Carter *et al.* 1979; Bruce *et al.* 1988). Moody *et al.* (1995a) considers the higher values of Carter *et al.* 1979 and Bruce *et al.* 1988 are due to the omission of Na from the CAR equation.

While CAR may be reduced substantially by the addition of fertilisers this effect is usually offset by an increased displacement of Ca from the cation exchange complex of soils by fertiliser cations (Moody *et al.*, 1995b). This buffering effect will depend on the effective cation exchange capacity of the soil and the relative calcium content. Soils with a moderate cation exchange capacity such as ferrosols are able to buffer the change in fertiliser cation addition.

1.2.3.5 Salinity

Low levels of salinity affect plant growth by reducing the water potential and restricting the plant's ability to absorb water (Winter, 1974). Higher salinities can directly inhibit root growth (Moody *et al.*, 1995a). Moody *et al.* (1995a) found a linear relationship between soil electrical conductivity (EC) and relative root elongation of soybeans across a wide range of soils and N and K fertiliser types. An EC of 4.1 dS m^{-1} was sufficient to reduce short term root growth of soybean seedlings by 10%. However, reductions in root elongation may become apparent before there are reductions in yield (Moody *et al.*, 1995a).

Potatoes are moderately salt sensitive (Winter, 1974) and Maas and Hoffman (1977) cited in (Marschner, 1986) found an average EC>2 dS m^{-1} in the soil solution was the threshold for yield decline in potatoes, with a 25% reduction in yield at 4 dS m^{-1}. Nadler and Heuer (1995) found an EC in irrigation water of 6 dS m^{-1} was sufficient to reduce marketable yield of potatoes. Reducing the proportion of highly soluble NO_3^- and K^+ in the starter bands should help reduce the EC of starter bands.

1.2.3.6 Cadmium

About 10-15% of Tasmanian Russet Burbank potatoes have a Cd content more than 0.05 mg kg^{-1} fresh weight (Sparrow and Salardini, 1997). However, in 1996 the Australian and New Zealand Food Authority increased the maximum permitted Cd concentration from 0.05 to 0.1 mg kg^{-1} fresh weight. Current evidence suggests that nearly all Tasmanian growers would meet the new requirement (Sparrow and Salardini, 1997). Tuber Cd increased proportionately with increases in the banded P rate compared to the broadcast P rate (Sparrow *et al.,* 1992), but was independent of fertiliser Cd content in a comparison of two band applied phosphorus fertilisers with high and low Cd concentrations (Sparrow *et al.*, 1993a). McLaughlin *et al.* (1993) evaluated the response of potatoes to four phosphorus sources: single super phosphate, rock phosphate, DAP and MAP. However, the sites were non-responsive to phosphorus and no effect on yield, Cd content, or tuber quality was found. The major effect controlling Cd accumulation in South Australia was the salinity of the soil solution, specifically its chloride content. This is less likely to be a causal factor in Tasmania where soil chloride levels in most potato growing areas are low. However chloride based fertilisers, such as KCl, can increase the mobility and hence uptake of Cd (Sparrow and Salardini, 1997). Chloride based fertilisers should be avoided where possible.

1.2.4 Other methods of fertiliser placement

Several alternative fertiliser application methods are available, including the application of fertiliser in seed coats and liquid seed treatments, as dissolved fertilisers in irrigation water and by foliar sprays. The relative merits and difficulties of each are discussed below, but none would appear to offer an improvement in fertiliser efficiency over band applied fertilisers.

1.2.4.1 Seed treatment

Several authors (Carter, 1967; Hathcock *et al.,* 1984; Scott, 1988) have used P coating on pasture and crop seeds. Scott (1988) concluded that seed coatings may be over four fold as effective as P banding, the response being greatest when soil phosphorus levels are low. Beneficial responses from seed coatings often occur at low levels of P and N; higher rates can cause toxicity and desiccation (Scott, 1988).

The potential benefits from nutrient seed coats applied to potatoes may include the diffusion of phosphorus and other nutrients directly into the tuber (Sharma *et al.*, 1977), locating the phosphorus closer to sites of early roots emergence (Costigan, 1984), and reducing the surface area of phosphorus in contact with soil (Lu and Miller, 1993). However, there are difficulties applying seed coats to potatoes and fertiliser injury to both tuber and new roots/shoots may occur (Sparrow 1998 unpublished).

Sharma and Gerwal (1989) showed savings of 25-50 kg P ha^{-1} could be made by soaking seed tubers in 0.4% phosphorus solutions. Phosphorus soaking was less effective when levels of soil-available phosphorus were higher. Barerjee *et al.* (1990) found responses to phosphorus soaking were less than an additional 25 kg P ha^{-1}. Pursglove and Sanders (1981) observed no yield increases from soaking. They believed this was due to leaching of the phosphorus from tubers before emergence.

Absolute quantities of 0.5-1 kg P ha^{-1} were absorbed by the tubers from the soaking treatment of Sharma and Gerwal (1989). The quantity of phosphorus absorbed depends on the metabolic activity of the tubers; non dormant tubers absorb more P. This would indicate storage of some phosphorus by active process within cells. Phosphorus soaking possibly elevates cellular phosphorus concentration, which then improves early root growth (Sharma and Gerwal, 1989). Soaking in phosphorus solutions may be viable if combined with fungicide or hormone treatments already given to tubers. The effectiveness of tuber soaking depends on both soil phosphorus status and the physiological state of the tubers. Alternatively, the phosphorus content of seed tubers could be increased by high fertiliser applications to seed crops. However, increasing the N content of seed tubers by higher fertiliser rates has proved difficult (Harris, 1978a).

1.2.4.2 Fertigation

Fertigation, the application of nutrients in irrigation water, has been trialed with potato crops (Papadopoulus, 1992; DeJong, 1997). Papadopoulus (1992) found the optimum fertiliser ratio of N, P, and K was 120, 40 and 130 mg L^{-1} respectively. This approximates to a ratio of 4:1:4, which is lower in phosphorus content than most fertilisers applied to potatoes, which tend to be around 1:1:1 (Marshall, 1984).

However, the annual application of phosphorus by Papadopoulus (1992) over a three year period was still 132 kg ha^{-1}, which is as high as required on other phosphorus fixing soils. Fertigation had not improved fertiliser efficiency. On average 22 kg ha^{-1} of phosphorus were removed annually in the 30-50 tonne crop giving a 17% phosphorus recovery efficiency. The root growth of drip irrigated crops is concentrated around the wetting zone (Bar-Yosef *et al.*, 1989). Soil nutrient levels under drip irrigation must exceed those for whole profile irrigation due to the reduced effective root volume (Bar-Yosef *et al.*, 1989).

1.2.4.3 Foliar sprays

The foliar application of P at up to 100 kg ha^{-1} increased yields of tubers over 60 mm diameter by 12% to 58 t ha^{-1} when compared to broadcast P (Lewis and Ketterwell, 1992). However, Sparrow *et al.* (1992) found that banding P fertilisers produced similar yield increases compared to broadcast fertiliser, indicating comparable yield responses can be obtained by band application alone. Singh and Kamath (1989) found foliar sprays to be the least effective phosphorus application method when compared to basal and split applications on canola.

Without complete canopy closure, a large proportion of foliar spray falls on the soil where it is of limited use to the crop (Pursglove and Sanders, 1981; Allison *et al.*, 2001). Micronutrient deficiencies are more suitably treated by foliar applications. The treatment of Fe and Mn deficiencies, at high pH, and Mo deficiencies in acidic soils are some examples where foliar applications have been successful (Marschner, 1986). Although up to 25% of applied foliar P may be absorbed within the leaf, only a small fraction, around 1% of the total applied P, is mobilised and able to move to other regions of the plant (Wittwer *et al.*, 1963). The foliar application of P does not appear to be any more efficient than soil applied P.

1.3 Soil properties and phosphorus reactions

1.3.1 Chemistry of ferrosols

Ferrosols are highly weathered soil derived from basic igneous rocks such as basalt and in some cases dolerite (Isbell, 1994). They are strongly structured soils, due to the presence of large amounts of aluminium and iron oxides. The strong structural

properties make them highly desirable for horticultural production, though there are some serious degradation problems occurring from the intensive use of these soils (Bridge and Bell, 1994; Cotching, 1995).

Clay contents in ferrosols are high, typically 50-80% in the topsoil, and tend to increase moderately through the subsoil (Bridge and Bell, 1994; Isbell, 1994; Moody, 1994). Ferrosols have a high organic matter content in the topsoil that decreases rapidly with depth. The organic matter in the topsoil significantly increases the cation exchange capacity and the chemical fertility of the surface layer of ferrosols (Moody, 1994). Organic matter content and soil acidity both tend to increase with higher annual rainfall (Isbell, 1994).

A summary of chemical and physical data of ferrosols is given in Table 1-2. Soil phosphorus properties change strongly with depth. There is a ten-fold reduction in available phosphorus from 84 mg P kg^{-1} in the topsoil to 9 mg P kg^{-1} in the subsoil, and a doubling of the phosphorus sorption index between the surface and subsoil. The accumulation of phosphorus in the topsoil reflects both the higher organic matter content (Jackman, 1955) and the very slow rate of movement of surface applied phosphatic fertilisers to lower depths in ferrosols (Murdoch and Nash, 1995). The increase in P sorption in the subsoil was correlated with elevated levels of citrate-dithionite extractable Al, due to the lower pH of the subsoil (Moody, 1994), and to sequestering of Fe and Al by organic colloids in the topsoil (Dubus and Becquer, 2002).

Kaolin and Fe/Al oxy-hydroxides are the prevalent clay minerals in ferrosols (Isbell, 1994; Moody, 1994). The Fe/Al oxy-hydroxides are responsible for their strong structural properties (Bridge and Bell, 1994) and they have a very high affinity for P (Moody, 1994). This effect is demonstrated by the phosphorus fertiliser requirements of ferrosols compared to other soil types (Table 1-3).

Table 1-2. Some chemical and physical properties of eight agricultural ferrosol soils (adapted from Moody, 1994)

Soil property	A Horizon		B Horizon	
	Range	Average	Range	Average
Clay (%)	26-66	56	47-78	68
Organic C (%)	1.0-4.5	2.5		
Effective CEC (cmol (+)kg^{-1})	3.5-12.3	8.1	1.5-10.6	5.5
pH w	5.1-6.5	5.9	5.1-6.5	5.8
PHBC	19-45	30	13-34	19
Colwell P (mg kg^{-1})	13-252	84	2-26	9
Phosphate sorption index	41-85	64	68-249	130
Citrate dithionite Fe (%)	4-16	10	7-16	10
Al (%)	0.2-1.8	0.9	0.3-1.8	0.8

Large application rates of P to potato crops are often recommended even when soil available P levels are high (Pitt, 1984); although Freeman *et al.* (1998) recommends a reduced P application rate if the Olsen soil test P level is greater than 40 mg P kg^{-1}. In general, P application rates in excess of 100 kg P ha^{-1} are recommended unless the available P levels are very high. Phosphorus responses are still achievable when Colwell P levels are greater than 210 mg P kg^{-1} (Sparrow *et al.*, 1992).

Table 1-3. Available phosphorus and fertiliser phosphorus requirement of potatoes grown on ferrosols and other soils.

Soil type	Soil test P (mg kg^{-1})	Recommended P rate (kg ha^{-1})	Reference
Coarse sand	Colwell[A] > 7.5	None	Maier *et al.* (1989)
Loam sand/clay	Colwell 30-40	None	"
Sand	Colwell 0-10	100	Hegney *et al.* (1989)
Sand	Colwell > 35	None	"
Sandy loam	Colwell < 40	75	Sparrow *et al.* (1993b)
Sandy loam	Colwell > 40	50	"
Low P fixing soil	Colwell > 13	None	Reuter *et al.* (1995)
Moderate P fixing soil	Colwell > 46	None	"
ferrosol	NA	100-120	Guerra *et al.* (1990)
ferrosol	Olsen<20	90	Strange and Marshall (1990)
ferrosol	Colwell <100	>150	Sparrow *et al.* (1992)
ferrosol	Olsen<8	150	De Jong (cited in Sparrow *et al.* 1992)
ferrosol	Colwell < 10	>135	Pitt (1984)
ferrosol	Colwell > 10	135	"
ferrosol	Olsen[B] < 5	160	Freeman *et al.* (1998)
ferrosol	Olsen > 40	50	"

[A] Colwell extractable P (Rayment and Higginson, 1992) [B] Olsen extractable P (Rayment and Higginson, 1992)

1.3.2 Soil phosphorus pools

Two factors can explain the phosphorus supply from a soil. These are the soil solution phosphorus concentration, referred to as the intensity factor, and the amount of readily adsorbed P, the quantity factor (Probert and Moody, 1998). Only a very small fraction of the soil phosphorus, less than 0.1%, exists in the soil solution. The quantity factor encompasses both mineral and organic phosphorus that is in equilibrium with the solution P and has potential to become available for plant uptake (Figure 1-1).

When fertiliser P is added to soil, it first dissolves into the soil solution. Then, depending on the cations and soil minerals present in the soil, P is precipitated or adsorbed into the labile pool. This process continues until a new equilibrium is reached. Solution P depleted by plant uptake is replenished by phosphorus dissolved or desorbed from labile pools. In this way, the soil solution concentration is buffered by the quantity of phosphorus in labile forms. The ratio of intensity to quantity gives an indication of the soil's supply capacity for a given nutrient (Holford, 1997; Probert and Moody, 1998).

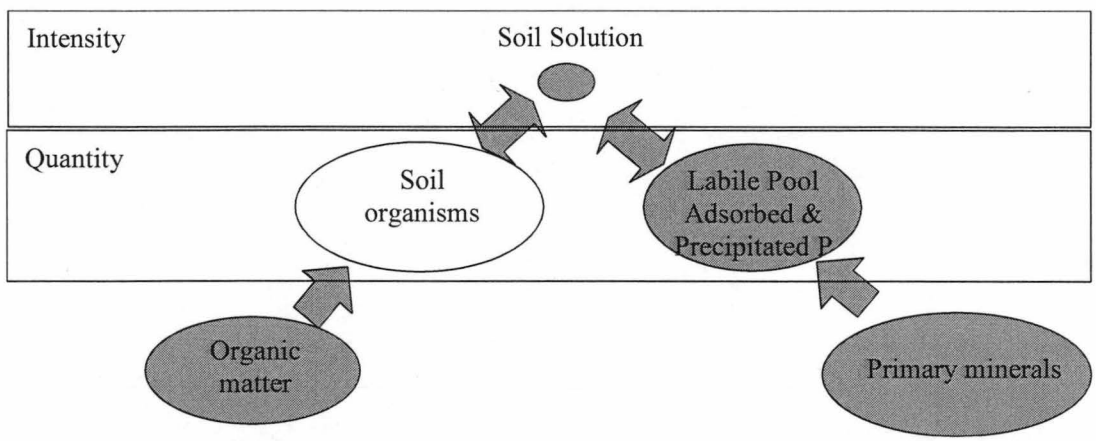


Figure 1-1. Soil phosphorus pools.

P occurs in both mineral and organic forms in the soil. The proportion of organic to inorganic phosphorus depends greatly on the phosphorus fixing qualities of the soil. Soils with a greater phosphorus fixation tend to contain a higher P content in the organic matter (Jackman, 1955). Organic carbon is an important component in the phosphorus cycle of soils. Substantial reserves of P may be held in organic pools,

which can be made available to the crop when the organic matter decomposes (Dormaar, 1972). The ratios of carbon to phosphorus in organic matter are more variable than C/N or C/S ratios (Jackman, 1964). C/P ratios are typically in the range of 0.01-0.02 but may be between 0.002 and 0.05 (Jackman, 1955; Walker and Adams, 1958). Hence, each 1% of organic carbon to a depth of 0.1 m contains between 100-200 kg P. Large seasonal fluctuations have been observed in labile P concentrations (Dormaar, 1972). These are often linked to periods of increased temperature when soils are moist, e.g. respiration of organic matter or following soil desiccation when the microbial population dies and microbial associated P is released. See also Section 1.3.3.3 p 21.

1.3.3 Soil phosphorus reactions

P fertilisers react strongly with soil minerals to form complexes that are only sparingly soluble. These reactions usually involve precipitation of the phosphate anion with polyvalent cations of metals like Al^{3+}, Fe^{3+}, Ca^{2+}, Mg^{2+} (Lindsay and Stephenson, 1959b) or its adsorption to hydroxy groups on the surface of iron and aluminium oxides (Moody, 1994). Ferrosols are formed from basalt deposits and are particularly rich in Fe and Al (Isbell, 1994) and, and as a result, have amongst the highest phosphorus fixing capacities of all soils (Moody, 1994).

Fixation of P is a complex and variable process. At low phosphorus concentration, phosphorus fixation is by adsorption to clay minerals, while at high phosphorus concentration, phosphorus is precipitated as low solubility crystalline products (Lindsay *et al.,* 1989). However, there is an arbitrary separation between the two modes. Adsorption continues at high phosphorus concentration, but because the rate of precipitation increases greatly once solutions become saturated, precipitation is the dominant form of phosphorus fixation at higher concentration.

1.3.3.1 Sorption at low phosphorus concentration

Unlike the simple electrostatic forces involved in cation exchange, anion adsorption involves more complex and durable reactions (Bohn *et al.,* 1979). Although electrostatic interactions occur between clays and anions, the capacity of some clay minerals to adsorb anions greatly exceeds the net positive charge of the soil. This type of adsorption, known as specific anion adsorption, is the process whereby most

fixed phosphorus is retained on acidic soils (Bohn *et al.*, 1979). Specific adsorption involves the exchange of anions with hydroxyl ligand groups on the clay minerals. Kaolin and the Fe/Al oxy-hydroxide minerals, the most prevalent minerals in ferrosols (Moody, 1994), both have large surface areas with exposed hydroxyl groups that can readily participate in ligand exchange with anions (Spotsito, 1989).

Phosphorus sorption is thought to occur by two processes commonly referred to as the fast and slow reactions (Bohn *et al.*, 1979). The fast reaction occurs within one to three hours in a high phosphorus fixing soil and involves a combination of non specific adsorption and specific ligand exchange. Slow reactions are responsible for the gradual reduction in available phosphorus (Bohn *et al.*, 1979). Several reaction mechanisms are possible for the slow reaction. These include solid state diffusion of phosphorus into the adsorbing particle (Barrow, 1987), diffusion of phosphorus through micropores (Bohn *et al.*, 1979) and the simultaneous dissolution and precipitation of clay minerals with phosphate (Bohn *et al.*, 1979). Slow diffusion has been implicated as the most likely sorption process operating in oxisols (ferrosols) (Wan and El-Swaify, 1998).

1.3.3.2 Precipitation at high phosphorus concentration

Phosphorus readily forms precipitates with calcium (Bell and Black, 1970; Bouldin and Sample, 1959; Lehr and Brown, 1958). The compound $CaHPO_4.2H_2O$ can precipitate in saturated mono-calcium phosphate solutions in the absence of soil (Lindsay and Stephenson, 1959a). This precipitation was found to be the major reaction governing the concentration of solution phosphorus at high phosphorus concentration from mono-calcium phosphate solutions. Taranakites, precipitates of NH_4^+ and K^+ with P may also form in conjunction with other cations, such as Fe^{3+}, Al^{3+} or Ca^{2+}, when NH_4^+ and K^+ are banded with phosphorus (Adams, 1980). The calcium phosphates and taranakites are formed in alkaline conditions (Barber, 1995). They are moderately soluble and are considered as slowly labile phosphorus (Lindsay *et al.*, 1959).

Variscite $Al(PO_4)_3$ and strengite $Fe(PO_4)_3$ are phosphate precipitates that form under acidic conditions (Hsu, 1982; Lindsay *et al.*, 1959). Variscite and strengite become increasingly less soluble at high pH (Figure 1-2). The high phosphorus

concentrations needed for variscite and strengite to occur are only likely to be found in fertiliser bands (Hsu, 1982; Lindsay *et al.,* 1959). At low temperature and low solution concentrations, amorphous Al-PO_4 tends to form (Hsu, 1982). Phosphate contained in variscite and strengite precipitated around acidic fertiliser bands should become soluble when the pH is increased once more.

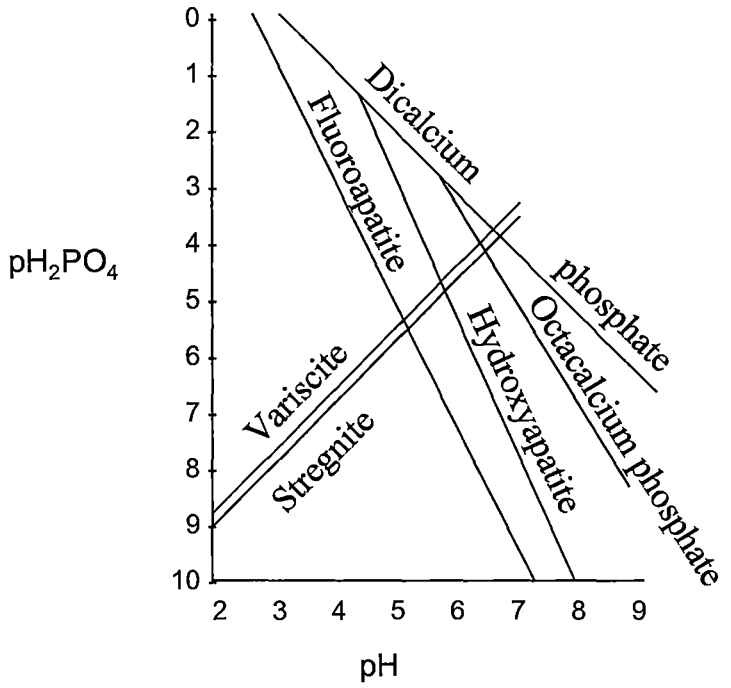


Figure 1-2. Solubility diagram for phosphorus compounds at 25 °C, 5 (mmol) Ca, (adapted from Lindsay and Moreno, 1960).

1.3.3.3 Organic matter

Soil organic matter is a complex material that includes a range of forms from recently applied plant debris to highly residual humic compounds (Black, 1957). Organic matter can affect soil phosphorus retention both indirectly by its effects on soil pH (Moody , 1994) and directly by the competition of organic anions with phosphorus for sorption sites (Deb and Datta, 1967; Ierich and Ohno, 1997; Iyamurewye and Dick, 1996; Moshi *et al.,* 1974), and by the complexation of polyvalent cations (Conyers, 1990; Curtin, 2002). Higher organic matter contents increase the negative charge of soil (Moody, 1994) which repels orthophosphate from colloidal surfaces thereby reducing phosphorus adsorption (Jungk and Claassen, 1997).

Returning crop residues to soils may increase phosphorus availability to subsequent crops (Ierich and Ohno, 1997). Green manures are the best source of organic anions since they are readily decomposable, the microbial activity is greater and more carboxylic acids are produced from actively growing compared to lignified material. Mature crop residues are only slowly decomposable and contain more lignified, inert, material (Moody, 1994) and hence have less effect on soil P. Soil structure is also improved by organic matter and larger aggregates have a lower surface area that may contribute to a correspondingly lower P fixation capacity (Wan and El-Swaify, 1998) (see also Section 1.3.5 p 25).

1.3.3.4 Soil pH

Raising the soil pH alters the surface charge of ferrosols, and other soils with a large amount of pH-dependent surface charge (Moody, 1994) (Figure 1-3). Although net charge in the topsoil becomes negative above pH 3.5, positive charge, responsible for some phosphorus fixation, only approaches zero at pH > 4.5. The greater amount of negative charge in the topsoil is due to a higher organic matter content, while in the subsoil with lower organic matter content, there is still positive charge at pHs > 6. These effects are mirrored in the higher sorption indices for ferrosol subsoils (Table 1-2).

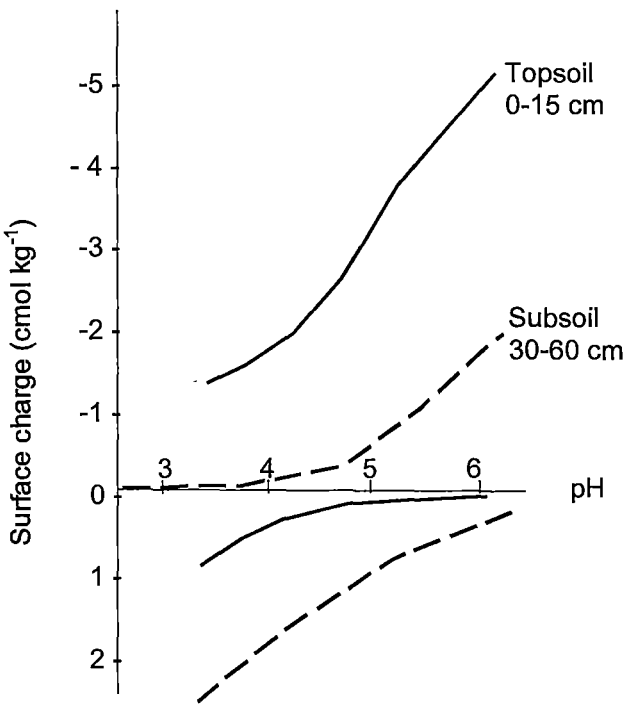


Figure 1-3. Surface charge (cmol kg^{-1}) changes with pH of a ferrosol from north Queensland, (adapted from Gillman (1984) in Moody, 1994).

Phosphorus sorption often decreases when soil pH increases from acidic to slightly acidic conditions, then increases again when the pH becomes neutral and higher (Barrow, 1987; Holford, 1983). The influence of pH on phosphorus retention or release depends on both the mineral and organic pools of P. Low carbon (C) to P ratios favour mineralisation of organic phosphorus, while high ratios support immobilisation of P in organic forms. Russell (1973) suggests C to P ratios, though more variable that C to N ratios, should be around 100:1-2. However, the C to P ratio can be increased in soils with higher P fixing properties (Jackman, 1955) (see also Section 1.3.2 p 18). Raising an acid soils pH through liming creates a more favourable environment for organic matter mineralisation and thereby releases P held in organic forms into mineral P forms (Haynes, 1982).

At pH 7 and higher, di-hdyrogen phosphate deprotonates to mono-hydrogen phosphate. The resulting additional negative charge, increases the affinity of the phosphate ion to the remaining positively charged adsorption sites (Barrow, 1984). This effect moderates the expected reduction in phosphorus adsorption from the increased pH.

Phosphorus reacts strongly with calcium and other polyvalent cations and increasing the Ca activity such as by lime application may induce Ca-PO_4 precipitation (Barrow, 1984; Bell and Black, 1970). Hence when $Ca(OH)_2$ was used as the liming material, sorption decreased when pH increased from 5.5-6 but precipitation increased above pH 6 (Naidu *et al.,* 1990) (Figure 1-4); whereas when KOH was used as the liming material, phosphorus sorption continued to decrease with increases in pH above pH 6 (Figure 1-4), (He *et al.,* 1997; Naidu *et al.,* 1990). The higher activity of Ca is responsible for the increase in P precipitation at pHs above neutral.

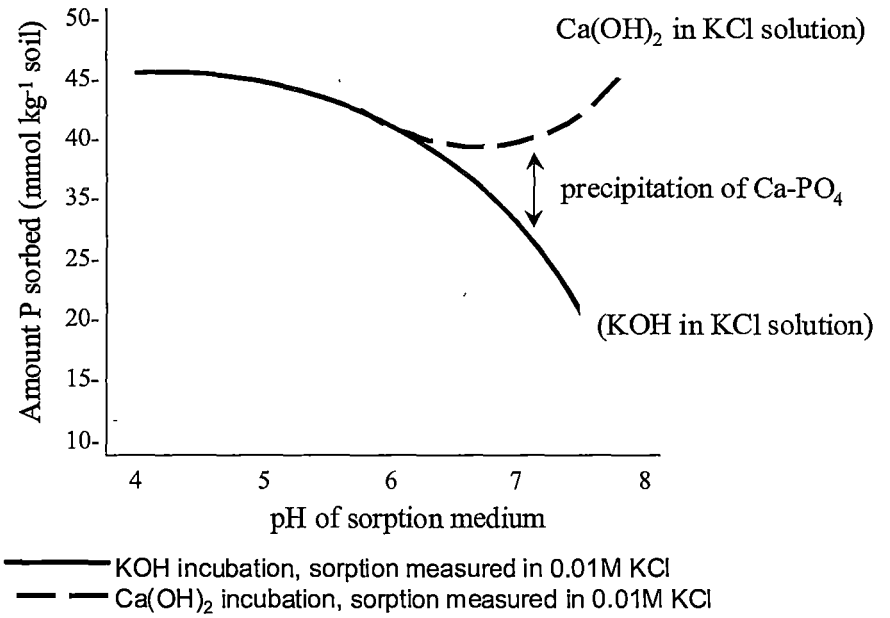


Figure 1-4. Effects of liming m a terial and cation species on phosphorus sorption (adapted from Naidu *et al.*, 1990).

1.3.4 Phosphorus diffusion in soils

Before phosphorus is available for plant uptake it must first be transported from within the soil or soil solution to the plant root. Plant acquisition of nutrients occurs by either the interception of nutrients during root growth, or through the mass flow of nutrients in the soil solution. Nutrients that are intercepted by the root are taken up directly into the root or may first diffuse short distances from the soil (Jungk and Claassen, 1997). Mass flow, where the nutrients are brought to the root in convective currents of soil solution used by the plant for transpiration (Jungk and Claassen, 1997), is a significant source of uptake only when the concentration of the ion in soil solution is high in relation to the needs of the plant, e.g. Ca, Mg, and nitrate. Ca and Mg may be in such excess quantities in the soil solution that they form precipitates on root surfaces (Barber, 1995). Ions that interact strongly with soil colloids, such as phosphorus and to a lesser degree ammonium and potassium, are in low concentrations in the soil solution, and reach the root predominantly by diffusion (Jungk and Claassen, 1997).

The rate of phosphorus diffusion in pure water is around 10^{-5} cm^2 s^{-1} (Jungk and Claassen, 1997). Within soil this rate is reduced by three to six orders of magnitude to around 10^{-8}-10^{-11} cm^2 s^{-1} due to the interactions of phosphorus with the adsorbing

surfaces of soil and the tortuosity of the path through soil (Jungk and Claassen, 1997). The actual rate of diffusion, know as the effective diffusion, D_E, depends on the properties of the soil, where D_E = D aqueous x (volumetric water content) x (tortuosity)/(buffer power). D_E can be increased by as much as 25 times over a typical range of soil volumetric water contents (Jungk and Claassen, 1997). Hence, soil moisture will strongly affect P diffusion and subsequent plant uptake of P.

The ionic environment in fertiliser bands also influences the diffusion of phosphorus. The diffusion of P increases in the order $H_2PO_4^-$>HPO_4^{2-}>$CaHPO_4$ (Lewis and Quirk, 1967). Hence increasing the pH, which deprotonates the phosphate ion from H_2PO_4- to HPO_4^{2-}, decreases P diffusion. Co-diffusion in ion pairs, e.g. NH_4^+ and PO_4^{3-}, increases the rate of diffusion (Peaslee and Phillips, 1970). While precipitation of phosphorus minerals, such as $Ca_3(PO_4)_2$, reduces diffusion (Bouldin and Sample, 1959; Moody *et al.,* 1995c). Bell and Black (1970) found the diffusion of phosphatic fertiliser sources to increase in the following order; DAP>MAP>MCP. The increasing diffusion follows the same order as their saturated solution pHs of 8.00, 4.00 and 1.48 respectively, indicating that acid soluble cations (such as Al^{3+}) retard diffusion. The presence of NH_4^+ from DAP would reduce phosphorus sorption by ion pair formation (Barrow, 1984), while MCP forms di-calcium phosphate precipitates (Aitken and Hughes, 1980). However, Aitken and Hughes (1980) believed the greater diffusion of ammonium phosphates resulted eventually in more phosphorus being fixed since a larger volume of soil was contacted by the P solution.

Soil phosphorus buffer power can vary between 100-2000 μm P g^{-1} and is a major influence on the diffusion of phosphate in soil (Jungk and Claassen, 1997). The tortuosity of a soil increases in proportion to the fineness of soil texture hence diffusion is reduced in clay soils compared to sands (Vegh *et al.,* 1989), though soil structure also has an influence. Ferrosols, with their high phosphorus affinity and high clay contents, will have a relatively low D_E, though the strong structural development present in ferrosols reduces the tortuosity and consequently improves P diffusion.

1.3.5 Soil aggregation

The degree and nature of soil aggregation has implications for the chemical (Wan and El-Swaify 1998) and hydrological properties of the bulk soil (Radulovich *et al.,*

1992). Well aggregated soils can be considered as a collection of discrete soil aggregates surrounded by a matrix of more or less connected inter-aggregate pores (Tamari, 1994; Gupta *et al.,* 1989). Inter-aggregate pores are usually in the size range of 30-1000 ¼m whereas the intra-aggregate pores are 10-0.1 ¼m (Hamblin, 1987). Hence, there is a distinct bimodal distribution of pores in an aggregated soil (Gupta *et al.,* 1989). In non-aggregated soils macropores tend to be disconnected, though long macropore chains may exist, and are surrounded by a matrix of soil (Radulovich *et al.,* 1992).

Upon wetting an aggregated soil, water is drawn into the aggregates by matric suction of the smaller intra-aggregate pores. Significant water conductivity usually occurs once the inter-aggregate pores fill and a water film develops over the surface of the aggregates, but by-pass flow can occur before the inter aggregate pores are filled (Radulovich *et al.,* 1992). When the rate of water influx is increased the thickness of the film increases, thereby increasing the hydraulic conductivity. Chemically, the most important component of an aggregated soil is the surface of the aggregates, since almost all of the water movement in aggregated soils occurs along this boundary (Wan and El-Swaify, 1998).

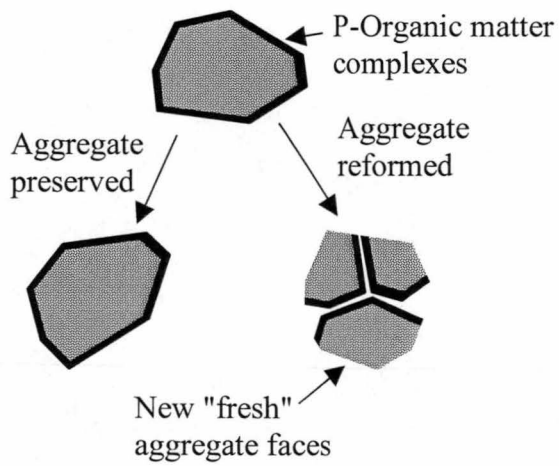


Figure 1-5. Aggregate preservation and reformation.

Ferrosols are highly aggregated soils (Isbell, 1994), hence fertiliser P diffusing into the soil solution initially reacts with clay particles at the aggregate surface. This reactive surface layer on aggregates is in the order of 200 µm thick (Linquist *et al.,*

1997). Over long periods of time, P sorbed on outer layers may slowly diffuse to layers deeper in the aggregate (Linquist *et al.,* 1997; Wan and El-Swaify, 1998)

Excessive cultivation may shatter and reform soil aggregates, which would expose "fresh" faces with a potentially high P fixing capacity (Figure 1-5). It may be possible to reduce the phosphorus fixing capacity of a soil by preserving large and stable soil aggregates. Large aggregates are formed by the coalescence of micro aggregates in an organic matter matrix (Elliot, 1986). Maintaining aggregate integrity through organic matter inputs may help reduce P fixation.

1.4 The potato plant, its growth and phosphorus requirements

1.4.1 Growth and development

Potato sprouts usually emerge within two weeks of planting (Figure 1-6). The rate of sprout development depends mostly on the soil temperature, although additional moisture and nutrition can promote sprout growth (Moorby, 1978). The optimum temperature for sprout growth is 20-25°C (Baerug and Steenberg, 1971). Sprouts initiated prior to planting are more likely to develop into dominant shoots and are able to suppress the development of still dormant sprouts. Physiological age also affects the growth rates of sprouts. The sprouts on older tubers grow faster but exhibit less dominance over other sprouts (Moorby, 1978).

Initially there is a net efflux of carbohydrates and nutrients from the sett until the plant develops sufficient leaf area, about 200-300 cm^2 (Moorby and Milthorpe, 1975) to supply its own carbohydrates (Harris, 1978a; Rowe, 1993). Carbohydrates produced before tuber bulking are used to increase the size of the plant (Beukma and VanDerZaag, 1990). Tuber initiation coincides with the emergence of inflorescences, and is induced by short day length and low soil temperature (Okazawa, 1967 cited in Sattelmacher and Marschner, 1978). Temporary N withdrawal, induced by low soil temperatures or nitrate leaching, may initiate premature tuberisation (Sattelmacher and Marschner, 1978).

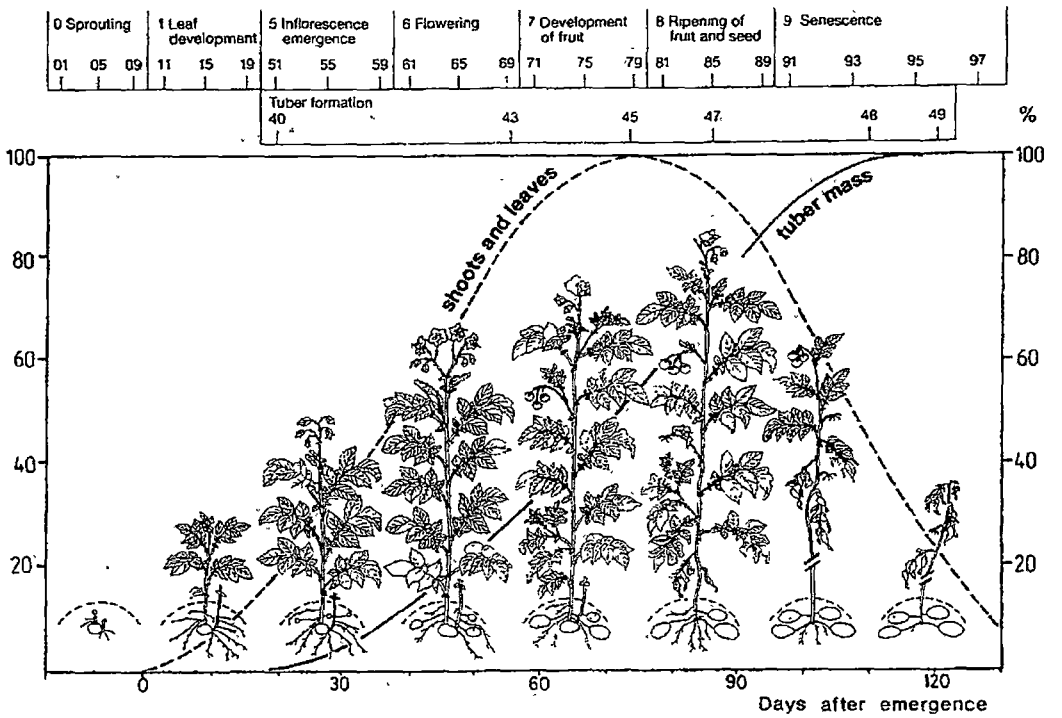


Figure 1-6. Development of the potato plant (adapted from Hack *et al.* (1993) in Klobe and Stephan-Beckmann, 1997a).

Tubers become the dominant sink for carbohydrates and nutrients from about two weeks after tuber initiation (Harris, 1978a). The onset of senescence may be influenced by nutrition. Inadequate P delays maturity (Ozanne, 1980), while high P promotes tuber initiation and earlier senescence (McCollum, 1978). High nitrogen levels retard tuber initiation and promote vegetative growth (Harris, 1978a), delaying senescence (Marschner, 1986) and potentially reduce yields.

The potato plant can be distinguished into three parts (Baerug and Steenberg, 1971):

1. The haulm, consisting of the leaves, stem and flowers, is the arial part of the plant except for the small underground part of the haulm reaching to the seed tuber.
2. Roots, which in the case of plants grown from seed tubers, develop from the nodes of the stem and stolons. Seedlings initially develop a taproot, which later becomes fibrous.
3. Tubers, includes the tubers and the stolons which emerge from leaf axils on the underground region of the haulm. Each tuber is formed from an enlarged section of stolon, see Figure 2-4.

Since the roots are the primary organ through which nutrients are intercepted and acquired, their development and physiology shall be discussed in more detail.

1.4.2 Root development

Root growth begins immediately after planting from tubers with active sprouts (Beukma and VanDerZaag, 1990). Roots growing from seed tubers form an adventitious root system directly off nodes on the main shoot (Cutter, 1978) while seed grown plants develop a tap root system (Marschner, 1986) which later becomes fibrous (Moorby, 1978). Robins *et al.* (1967) describe potato root systems as developing from one to two dominant roots from each bud and that roots emerging from buried nodes are rare. In cv. Russet Burbank, which is the main processing potato variety grown in Tasmania, adventitious roots emerge first from the lowest node of the stem, and then continue to develop sequentially up the stem (Gracie, 1995). Roots do not develop from dormant eyes on the sett (Moorby, 1978).

Potato roots first emerge from above the seed tuber, directly off the shoot. Although the most likely sprout to develop on a sett is from the uppermost eye (Beukma and VanDerZaag, 1990), sprouts from the sides and bottom of setts may also develop. However, the range of positions from which sprouts may emerge makes choosing the ideal location of a starter band difficult. As a compromise the best location for early interception of starter fertilisers would be just beside and above the seed tuber. This would enable an early interception of starter fertilisers by plants with roots developing from the top of tubers while those with roots growing from below the tuber have less distance to reach the conventionally banded fertiliser, placed 50 mm below and 50 mm beside the sett.

There is considerable variation in the pattern of root development, particularly between early and late maturity types, with later maturing cultivars developing larger root systems (Iwama, 1998). There tends to be an inverse effect of the number of sprouts on root weight. Competition occurs between shoots and roots for limited seed resources, most likely to be carbohydrates, since increasing the mineral nutrition around seed tubers does not alleviate competition (Morris, 1967).

Potato roots do not readily grow below soil temperatures of 10°C (Epstien, 1966; Sattelmacher and Marschner, 1978) (Figure 1-7). Maximum root development occurs at 20-25°C (Beukma and VanDerZaag, 1990; Sattelmacher and Marschner, 1978), but the highest tuber yield is obtained at slightly lower temperatures. This is due to a reduction in respiration rate and an earlier onset of tuber initiation at lower temperature (Beukma and VanDerZaag, 1990).

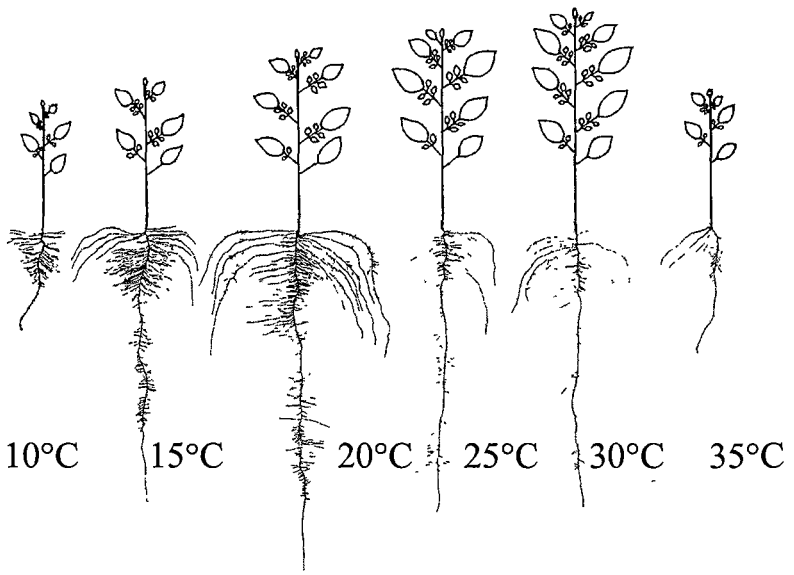


Figure 1-7. Effects of tempera ture on root and shoot growth of potato seedlings (adapted from Marschner 1986).

The distribution of roots is affected by soil temperature. In a heated soil, potato roots were found to grow deeper than in unheated soil (DeRuijter *et al.,* 1996). Similarly, corn plants have been shown to grow roots at a more vertical angle in warmer soils (Mosher and Miller, 1972). The growth patterns of potato roots observed by Kleinschmidt, (1983) and Weaver *et al.* (1922), where roots grew horizontally close to the soil surface, may have been caused by cooler temperatures in the underlying soil layers (Mosher and Miller, 1972; Rab and Willatt, 1987). Hence, fertiliser positioning may need to account for differences in soil temperature.

Approximately 90% of potato roots from mature plants occur within 200 mm either side of the sett (Rab and Willatt, 1987). Maximum root length occurs at relatively

shallow depth, 100-150 mm (Lesczynski and Tanner, 1976; Rab and Willatt, 1987) with more than 90% of roots in the 0-300 mm depth range (Myers, 1984; Rab and Willatt, 1987). Rooting depth can be restricted by subsoil compaction (McDole, 1975; Sojka *et al.,* 1993), lateral compaction (DeRoo and Waggoner, 1961), and waterlogging (Myers, 1984). Although deeper rooting, down to 1 m, can occur in well structured soils (Kutschera, 1960), the root density at such depths is low and nutrient and water uptake from these roots is not likely to contribute much to the overall requirements of the plant. Maximum root density is reached after about 50 days from planting (Pursglove and Sanders, 1981; Rab and Willatt, 1987).

Root distribution and phosphorus uptake are also affected by soil texture. Phosphorus was found to be removed in equal amounts from within, below and to the side of hills in sandy soils but proportionally more phosphorus was removed from within the hill by potato plants in clay soil (McCorquodale and Moorby, 1968; Newboulder *et al.,* 1968 *cit* in Harris, 1978a). This probably reflects the greater capacity of the clay soil to supply both phosphorus and moisture. Clay soils may also be more prone to compaction, which may limit root growth into the sides of hills. Root growth can be increased by compaction in sandy soils (DeRuijter *et al.,* 1996) but decreases when heavier texture soils are compacted (Iwama, 1998; Vos and Groenwold, 1986).

The root systems of potatoes are less extensive than other crops (Jacob *et al.,* 1949; Pursglove and Sanders, 1981). Management practices to increase root proliferation by limiting compaction should be encouraged.

1.4.3 Plant P Uptake

Plants may increase nutrient uptake by root proliferation (Smyth and Cevalier, 1984), or by increased nutrient uptake efficiency from existing roots (Jungk and Claassen, 1997). Increases in the P uptake rate can be substantial but are not in direct proportion to the increase in solution P concentration (Jungk and Claassen, 1997). Some plants are adapted to low soil phosphorus diffusion rates and increasing the solution phosphorus concentration does not increase P uptake (Barber, 1980). The concentration of phosphorus in the zone near fertilisers may be so high that the uptake rate of many plants becomes saturated (Marschner, 1986). Such increases in

the nutrient concentration will not immediately benefit the plant; however, the additional nutrient may be useful if the plant can acquire it during later growth stages.

Root proliferation increases the uptake of P by the greater surface area in contact with fertilised soil. Phosphorus uptake can be further improved by the presence of root hairs, which extend from just behind the root tip to where the exodermis is formed and may be up to 0.1 mm long. It is the extra distance root hairs reach into the soil, not the additional surface area, that is responsible for the increase in P uptake. Hence, the benefit of root hairs depends on the relationship between effective diffusion (D_E) (Section 1.3.4 p 24), and the root hair length. Root hairs must be at least as long as D_E to have significant benefit (Jungk and Claassen, 1997). Since D_E is low in ferrosol soils, root hairs may be beneficial for the uptake of soil P. However, potato roots do not appear to form root hairs under normal growing conditions (personal observation) and their presence was not reported by Cutter (1978) or Kratzke and Palta (1985).

Phosphorus uptake occurs along a greater length of the root than most other nutrients, (Barber, 1980) and may remain high after the endodermis has formed (Ozanne, 1980), hence the ageing and suberisation of roots does not exclude phosphorus uptake. Higher soil temperatures increase P uptake from the apical region by stimulating cell growth and the P uptake rate (Marschner, 1986). Uptake of mono-valent $H_2PO_4^-$ is up to ten fold greater than di-valent HPO_4^{-2}, hence raising the pH reduces plant phosphorus uptake (Barber, 1980).

1.4.3.1 Responses of roots to nutrition

Root length density, a measure of the length of root per volume of soil, tends to decrease exponentially with soil depth (Greenwood *et al.,* 1982). Hence the greatest uptake efficiency of strongly buffered nutrients, such as P, is in the surface layers and in the period before the plant begins the reproductive phase, after which the roots begin to senesce (Barber, 1995). Nutrients that are absorbed by mass flow, such as nitrate, can still be efficiently absorbed deeper in the soil where root length density is lower, provided there is adequate moisture (Jungk and Claassen, 1997). However, this is often only a minor source for the nutrient.

Nitrogen has a strong influence on root proliferation. Localised placement or banding of fertiliser N and P stimulates nearby root growth (Drew, 1975; Miller and Ohlrogge, 1958; Robinson, 1994). To achieve a beneficial response to banded P both nitrogen and phosphorus must be intimately mixed (Blanchar and Caldwell, 1966a). Sattelmacher (*cit* in Marschner, 1986) found differences in potato root growth to different N sources. Nitrate increased the size of the root system while ammonium increased the incidence of root branching (Figure 1-8). Ammonium N would be a better N source to facilitate P uptake, due to the increase in localised root branching. Acidification, by exchange of H^+ for NH_4^+ absorbed by the plant roots, can increase the dissolution of phosphorus (Riley and Barber, 1971) and increase the rate of uptake of phosphorus due to an increase in the proportion of $H_2PO_4^-$ to HPO_4^{2-} (Hagin and Tucker, 1982; Barber, 1980). Some ammonium N should be included with the starter fertiliser to promote root proliferation.

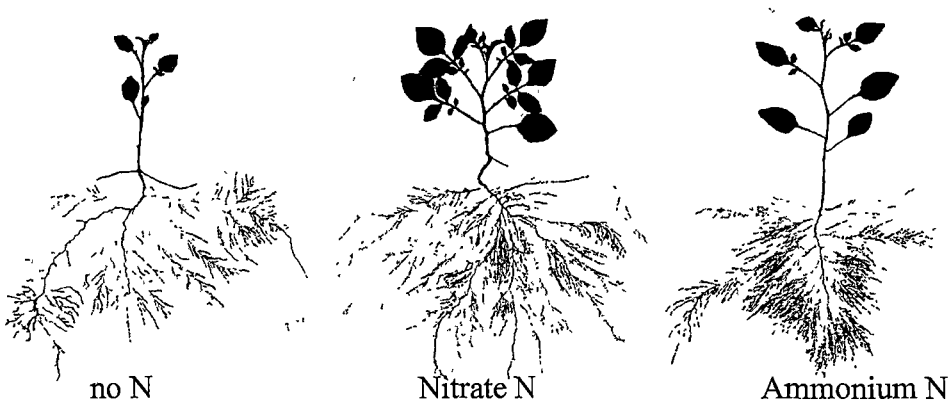


Figure 1-8. Potato seedling root growth in sandy soil with nitrate and ammonia nitrogen sources (adapted from Marschner, 1986).

1.4.4 Phosphorus nutrition of potatoes

The phosphorus content of seed tubers changes little during the period from planting to emergence. Changes that do occur are attributed to nutrient leaching and the respiratory loss of carbohydrates (Moorby (1968). After emergence, the concentration of phosphorus in both the tuber and developing shoots decreases due to dilution in the rapidly expanding tissue. The decrease in shoot P in potato tissue

follows a sigmoidal pattern, from about 0.6% at emergence to 0.2% at maturity, (Klobe and Stephan-Beckmann, 1997b; Harris, 1978a). The greatest decrease occurs in the first six weeks after emergence (Figure 1-9). Similar decreases in shoot phosphorus concentration were observed by Menary and Hughes (1967) in tomatoes.

Phosphorus concentration at maturity is lowest in the stem, about 0.2%, while the tubers and leaves contain about 0.3% phosphorus (Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b). The very high phosphorus requirement of potato at 30-45 days after emergence (Figure 1-9) coincides with the maximum shoot demand and the beginning of tuber bulking. After tuber initiation there is a net export of phosphorus from the shoot to the developing daughter tubers (Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b).

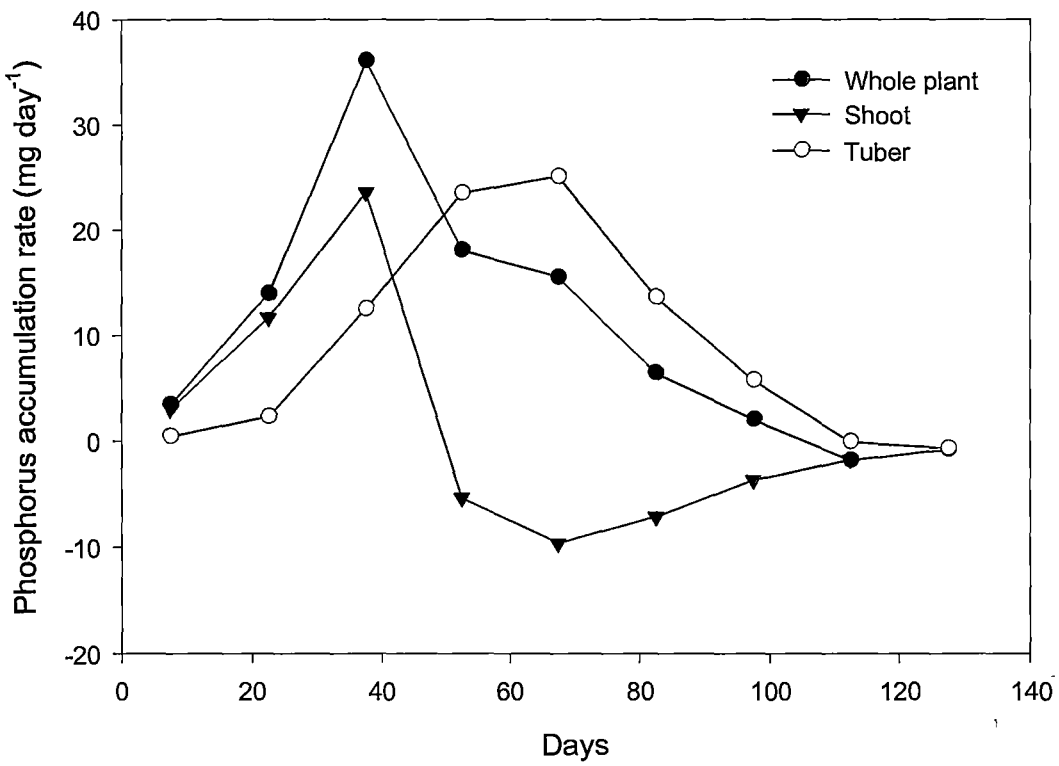


Figure 1-9. Phosphorus accumulation rates of the whole potato plant, shoots and developing tubers (adapted from Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b).

Fertiliser phosphorus placed at sowing is in contact with the soil for at least 30-40 days when only small quantities of phosphorus are taken up by the plant (Lorenz and

Vittum, 1980). However, due to the small size of the early root system, the plant relies heavily on the high concentrations of fertiliser phosphorus during early growth stages. After emergence there is a rapid decrease in the partitioning of fertiliser phosphorus to non fertiliser soil phosphorus due to the increasing size of the root system (Pursglove and Sanders, 1981). Phosphorus nutrition is therefore most important during the early growth stage, when the smaller root system places a greater dependence on fertiliser phosphorus than soil phosphorus (Pursglove and Sanders, 1981). Higher soil moisture contents can improve phosphorus fertiliser efficiency from an increase in the proliferation of roots (Rab and Willatt, 1987; Klepper *et al.,* 1983) and by improving P diffusion (Jungk and Claassen, 1997).

1.4.5 Response of potatoes to irrigation

Potatoes are highly sensitive to water stress (Asfary *et al.*, 1983; Harris, 1978b; Beukma and VanDerZaag, 1990; Martin *et al.*, 1992). Several linear relationships have been proposed to explain tuber yield response to irrigation (Table 1-4). In principle, transpirational loss should bear the closest relationship since this is a measure of stomatal conductance and hence the quantity of CO_2 assimilated (Rijtema and Endrodi, 1970). However, transpirational loss needs to be normalised to mean vapour pressure deficit which is difficult to measure.

Table 1-4. Relationship of potato tuber yield to measurements of irrigation application or irrigation use (yield response as tonnes per irrigation unit).

Yield response	Irrigation unit	Reference
0.1-0.2	mm of irrigation	(Harris, 1978b)
0.12	kPa soil water matric potential	(Taylor and Ashcroft, 1972)
0.58	mm transpired/(mean vapour pressure deficit)	(Rijtema and Endrodi, 1970).

Crops that produce vegetative storage organs, such as potatoes and sugar-beet, tend to have high transpiration rates until the final stages of growth (Figure 1-10) (Jensen, 1975). This is in contrast to grain crops that rapidly decrease transpiration during grain filling. Hence irrigation needs to be maintained right through the growing season of potato crops.

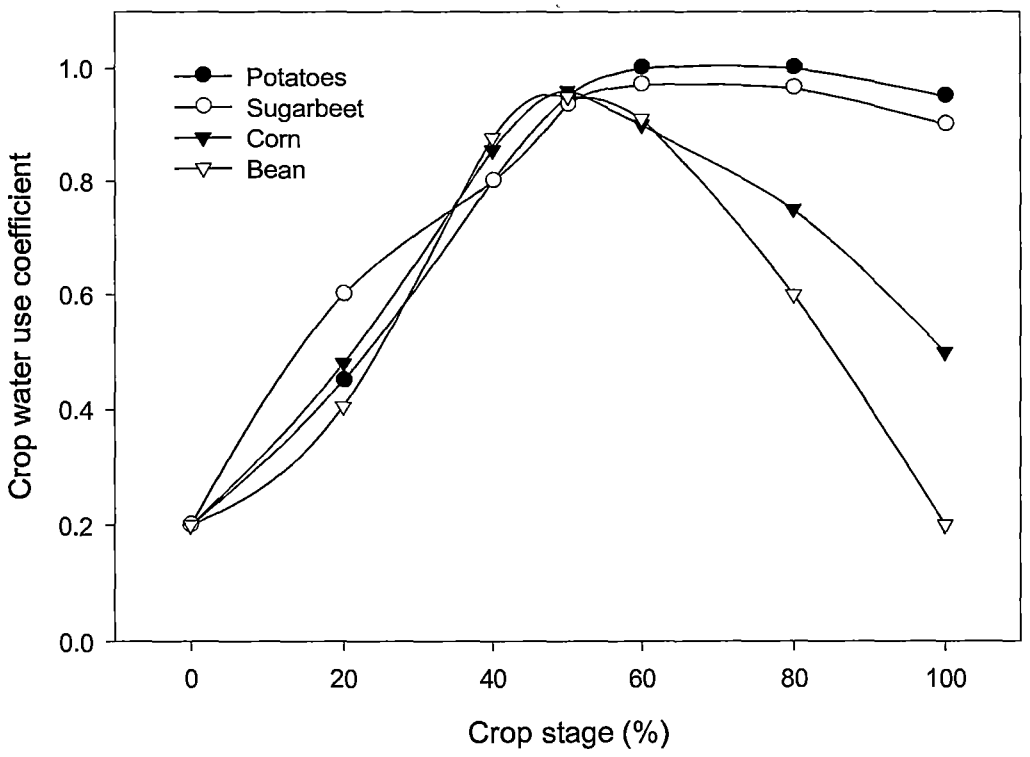


Figure 1-10. Crop water use coefficients of potatoes, sugar-beet, corn and bean, (adapted from (Hargraves, 1968) in Jensen, 1975).

Increasing the soil moisture status from low to medium improved phosphorus uptake by more than 60% (Baerug and Steenberg, 1971). Although the higher rates of irrigation improved the efficiency of broadcast fertiliser more than banded fertiliser phosphorus (Figure 1-11), banded phosphorus was always more efficient, regardless of the irrigation regime.

Banded phosphorus is located deeper in the soil where it is less subject to moisture fluctuation (Stieber and Shock, 1995). In dry seasons, deeper than normal banding can improve the response to banded P (Holliday and Draycott, 1968).

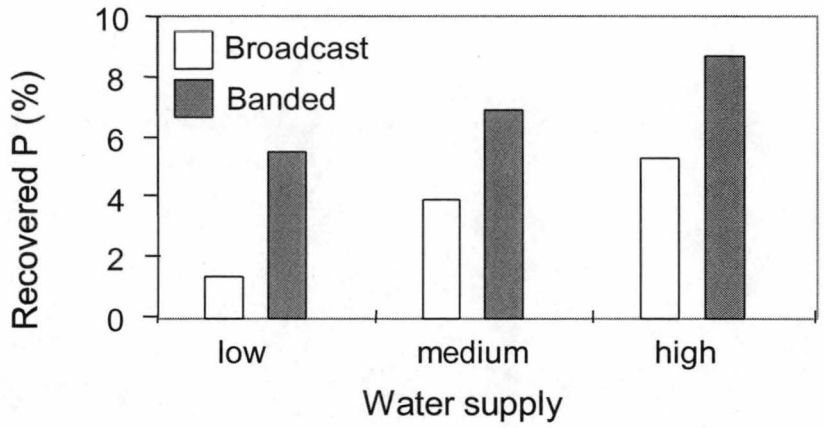


Figure 1-11. Effects of irrigation and phosphorus placement on phosphorus percentage recovered in the crop (adapted from Baerug and Steenberg 1971)

While phosphorus uptake is increased in proportion to irrigation intensity, the frequency and timing of irrigation has as much effect on the crop as the quantity of water used (Cotching, 1997; Harris, 1978b; Shock *et al.,* 1999). Both over and under watering can reduce yields (Cotching, 1997). Excessive irrigation reduces the nitrogen contents of plants by leaching of soil nitrates (Sparrow, 1994; Stark *et al.,* 1993; Stieber and Shock, 1995). In poorly drained soils excess irrigation reduces the proportion of air filled pores and limits the oxygen uptake of roots (Myers, 1984). Under-watering reduces uptake of phosphorus and other nutrients (Baerug and Steenberg, 1971; Ozanne, 1980). Hence, the desirable effects of irrigation are to dissolve the fertiliser (Blanchar and Caldwell, 1966a), to increase diffusion of phosphorus and other nutrients in the fertiliser (Jungk and Claassen, 1997), and improve the conditions for root growth (Barber, 1995; Rab and Willatt, 1987).

1.4.6 Methods for measuring root growth

The development of plant roots can be measured by destructive soil coring or trench profile methods and non-destructive rhizotron methods. Soil coring and trench profile methods allow the roots in a known volume of soil to be measured. These are useful for obtaining net root production, as root length per volume of soil, but yield no information on the rates of root growth (Thorupkristensen and Vandenboogaard, 1998). Total root production can only be measured by repeated measurements on the same group of roots (Majdi, 1996). Currently the best procedure for repeated measurements on roots is through rhizotron studies (Roland *et al.,* 1996).

Rhizotrons however, influence the growth of root systems. Roots intercepting the rhizotron wall are prevented from growing into the volume of soil occupied by the rhizotron and instead turn and grow along the soil rhizotron interface. This tends to increase the density of roots observed compared to soil coring, though not always, (Roland *et al.,* 1996). Correlations between coring and rhizotron studies can be quite high with sixteen out of twenty six studies having $R^2 > 0.7$ (Roland *et al.,* 1996). It is probably better to focus initially on net root densities obtained by trench profile methods. This should enable the timing and location of root growth in relation to fertiliser placement to be observed.

1.5 Suggested research

Phosphorus uptake is broadly related to root surface area (Adams, 1980), hence young seedlings with a small root surface area rely heavily on seed reserves of P and on soil and fertiliser P in close proximity to the emerging roots (Costigan, 1987). The current Tasmanian potato industry practice is to band fertilisers in two rows 50 mm beside and up to 50 mm below the seed potatoes (Anon., 1969; Hocking and Ireland, 1984; Regel, 1988). Since there is likely to be a moderate time delay between the initiation of root growth and root interception of the fertiliser, some minor phosphorus deficiency may occur during this time.

Researcher should be undertaken to identify P fertiliser strategies that achieve growth responses during the early growth stages, from emergence to tuber initiation. Such strategies may then have a beneficial influence on yield.

Starter fertiliser bands are separate bands placed close to the seed where full fertiliser bands would cause seed burn (Costigan, 1984). Phosphorus in starter fertiliser bands is intercepted earlier, when plant phosphorus demand is higher, and possibly before much phosphorus has been fixed by the soil. The additional phosphorus supply of the starter fertiliser may promote a more vigorous early growth (Laughlin 1977) and improve the overall phosphorus efficiency of the crop.

Small responses have been found from liquid fertiliser solutions applied before planting to seed tubers (Sharma *et al.,* 1977). Moderate irrigation x phosphorus

responses have also been observed (Baerug and Steenberg, 1971). There may be potentially beneficial responses to liquid starter fertiliser formulations and to different irrigation regimes. None of the other P fertiliser strategies (seed coatings, fertigation and foliar applications) would appear to be practical alternatives to soil placed P.

Most of the P acquired by the potato crop comes from soil pools with only small amounts derived from recent fertiliser sources (Pursglove and Sanders, 1981). Organic matter is an important source of soil reserves of available P in ferrosols and manipulating the soil P reserves by irrigation and organic matter incorporation may be a means to improve P uptake from soil pools. Recently applied phosphorus interacts with and can be retained on the surface of aggregates (Linquist *et al.*, 1997). Practices that preserve aggregate integrity and the organic matter coatings on aggregates may help reduce P fixation. Higher soil moisture levels and good aggregate structure could improve phosphorus diffusion from less labile soil P reserves.

An understanding of the pattern of potato root growth will enable the most appropriate location for starter fertiliser to be selected. Irrigation efficiency and the acquisition of residual nutrients from the soil are also affected by the pattern of root growth (Baerug and Steenberg, 1971; Hammes and Bartz, 1963; Prumel, 1957; Westermann and Sojka, 1996). Soil properties can strongly influence root development (Bishop and Grimes, 1978; DeRoo and Waggoner, 1961; Iwama, 1998; McDole, 1975; Rab and Willatt, 1987). Measuring the soil properties and root growth patterns of field grown potatoes will help develop a greater understanding of their role in plant nutrition.

2 Dry granular starter phosphorus

Tasmanian potato yields have increased over the last few decades (Matherson, 1999) which has largely been achieved through more effective crop management, particularly from improved irrigation practices (Stephens, 1979). Consequently, fertiliser rates have been increased to sustain the higher production (Stephens, 1979; Anon., 1969; Regel, 1988). However, to avoid fertiliser injury, fertilisers have had to be placed further from the seed. This practice has introduced the possibility of P and other nutrient deficiencies occurring during the early growth stages, particularly when soil temperatures are low. Low soil temperatures tend to reduce the growth rate of roots and the rate of nutrient uptake (Marschner, 1986).

Researchers in the USA (Kleinschmidt 1983) have found beneficial responses from potatoes to small quantities of P banded with the sett as a starter fertiliser. The response was attributed to the alleviation of P deficiency during crop emergence. Similar starter fertilisers have proved successful on other crops (Costigan 1984; Bednarz *et al.*, 2000; Bullock *et al.*, 1993; Gordon *et al.*, 1998; Guthrie, 1991; Hutchinson and Howard, 1997; Stewart and Edmisten, 1998; Stone, 1998). Hence there is potential for the use of a starter P fertiliser to either improve potato yield or to substitute for some of the conventionally banded fertiliser. This has not been thoroughly investigated in Tasmania, but may provide a means of reducing the quantity of P applied to potatoes. Field experiments were initiated to assess potato responses to rates of starter fertiliser up to 80 kg P ha^{-1} and 48 kg N ha^{-1} placed with the sett at planting. Additional information on the initial root growth pattern of potatoes was sought to ensure starter fertilisers were placed in the most appropriate location.

2.1 Field trial of granular starter phosphorus

2.1.1 Methods

During the 1998-1999 season two field trials were conducted in NW Tasmania, one at Forthside Vegetable Research Station the other on a farmer's property at Paloona, approximately 6 km south of Forth. Both trials used a factorial design comparing five rates of starter P, up to 80 kg P ha^{-1}, against five rates of conventionally banded

P, up to 240 kg P ha^{-1}, giving a total of twenty five treatments. Three replicates were used at Forthside and four at Paloona. Planting, harvest and tissue sampling dates are given in Table 2-2 p 43. Russet Burbank potato seed was used at both trial sites. Starter fertiliser of mono-ammonium phosphate (MAP) was applied at rates of 0, 10, 20, 40, and 80 kg P ha^{-1}, and conventional band-placed P, as triple super phosphate (TSP), at 0, 30, 60, 120, and 240 kg P ha^{-1} (Table 2-1). Conventionally banded fertiliser was placed in the standard banding position 50 mm below and 50 mm to the side of the sett in two rows (Figure 2-1). The starter fertiliser was placed in a single row just above and to the side, but in contact with the sett. At Forthside the starter fertiliser was placed by hand from preweighed containers of fertiliser, while at Paloona, starter fertiliser was placed through a hand-held seed drill that had been modified to distribute the required fertiliser rates. All plants received 200 kg N ha^{-1} and 300 kg K ha^{-1} in the conventional banding position.

Table 2-1. Fertiliser N, P and K rates (kg ha^{-1}) for the treatments in the field experiment at Forthside and Paloona in 1998.

Starter band		Conventional band			Total	
P	N	P	N	K	P	N
MAP	MAP	TSP	$(NH_4)_2SO_4$	KCl		
0	0		200	300	0	200
10	6		200	300	10	206
20	12		200	300	20	212
40	24		200	300	40	224
80	48		200	300	80	248
		0	200	300	0	200
		30	200	300	30	200
		60	200	300	60	200
		120	200	300	120	200
		240	200	300	240	200

Plots with starter bands received additional N of up to 48 kg N ha^{-1} for the highest starter P rate of 80 kg P ha^{-1}. The higher N rates of the starter treatments confounds the fertiliser placement effects with the N rate, but simplified the application of fertiliser rates. A third variable rate fertiliser box would have been required to adjust the N rates to an equivalent rate on all plots. Should a favourable starter response occur then further work would be necessary to separate P placement from N rate effects.

At both sites the furrows were closed by hand raking after planting, and the hills were formed up three to four weeks later. Each treatment plot was four rows wide by six metres long, the outside two rows being buffers, and there were half metre buffers at the start and finish of each plot. Petioles were sampled from the buffers and the inside two rows were reserved for the final tuber yield. At Forthside the previous crop was lupin followed by a regrowth lupin green manure crop that was incorporated eight weeks prior to planting. The trial site at Paloona had been under pasture for five years. Solid set irrigation was used at Forthside and a travelling irrigator at Paloona. The farm managers at both sites carried out crop husbandry. Soil samples, from (0-10 cm) comprising 20 subsamples bulked for each replicate in each trial, were collected two to three weeks prior to planting.

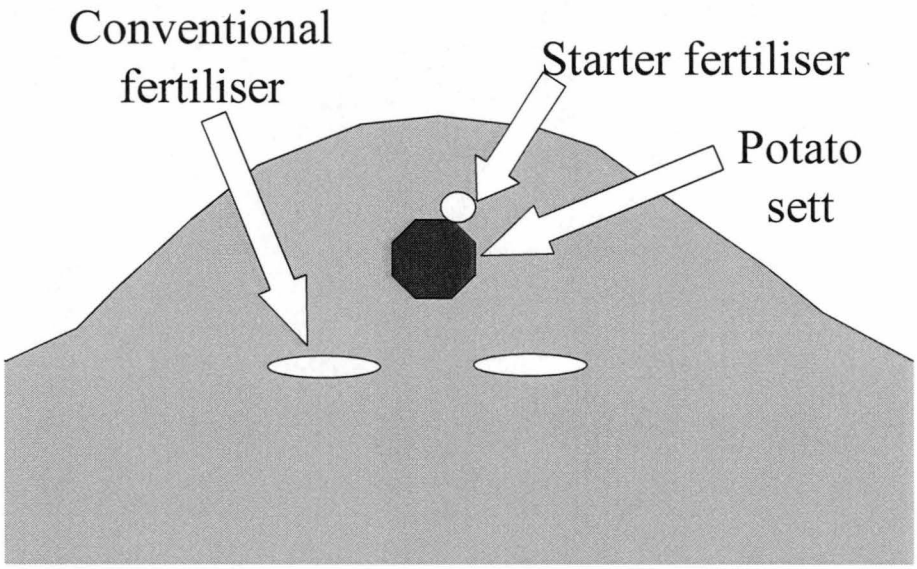


Figure 2-1. Location of conve n tional and starter bands used for all trial work.

Petioles were sampled three times at Forthside and twice at Paloona in 1998, but only once from subsequent trials (Table 2-2). Twenty petioles were taken from the 4^{th}-5^{th} leaves of each plot from the buffer rows. The stripped petioles were then dried, ground and digested in nitric acid prior to analysis by induction coupled plasma electron spectroscopy (ICPES). Prior to grinding, the dry weight of petioles was recorded to use as an index of plant biomass. This was a way of quantifying obvious biomass differences between the treatments without having to remove whole plants.

Table 2-2. Sowing, petiole sampling and harvest dates at all trial sites. Numbers in brackets are days after planting.

Crop stage	Forthside 1998	Paloona 1998	Forthside 1999	Forthside 2000
Sowing	16/10/98	22/10/98	04/11/99	09/11/00
0-5 mm tubers	26/11/98 (41)	-	06/12/99 (32)	-
10-20 mm tubers	30/11/98 (45)	27/11/98 (36)	-	21/12/00 (42)
20-40 mm tubers	07/12/99 (52)	04/12/98 (43)	-	-
Harvest	29/04/99 (195)	30/04/99 (190)	9/5/00 (187)	12/04/01 (154)

Potato tubers were dug by either single row harvester (1998 and 1999) or twin row harvester (2000). Once harvested, the tubers from each plot were packed into one or two sacks and stored for up to six weeks prior to grading. In 1998 the tubers were graded into five weight categories: 0-75 g, 75-250 g, 250-450 g, 450-850 g, and larger then 850 g. In 1999 and 2000 the 75-250 g weight category was split into two categories of 75-150 g and 150-250 g. Additional categories for tubers with secondary growth and other defects were included where necessary. These categories are grouped together and presented as reject yield.

A subsample of six to eight tubers was collected from each plot to be used for specific gravity measurement and tissue analysis. These samples were stored at 4°C until processing. Specific gravity was measured by the weight-in-air weight-in-water method (Anon., 1981). To measure tuber nutrient content, a longitudinal slice, approximately 5 mm thick, was cut from each tuber. The skin, to 0.5mm, was removed and the remainder diced and rinsed in distilled water. A 100 g subsample of diced tuber pieces was taken for oven drying at 60-70°C. The oven dry sample was ground and 0.5 g digested in nitric acid for ICPES analysis. Tuber nutrients were analysed from the Forthside 1998 and Forthside 2000 trials only. Tuber Cd was measured by atomic absorption spectroscopy from the Forthside 1998 trial site only. Samples for Cd analysis were digested in perchloric acid.

Results were analysed by a two way ANOVA factorial design comprising conventional P band rates and starter P band rates. The data for both sites were first analysed separately and then as a combined analysis of two sites using the structure Sites*Blocks*Treatment (Pearce 1983). Interactions between starter and conventional band rates were tested for, but none were found to be significant, no

interaction data is shown in the tables. Petiole nutrient data from the two sites were combined from the 10-20 mm tuber size data sampling time (Table 2-2).

Multiple linear regressions using the regression model Y = X1*conventional + X2*starter + C were applied to petiole P uptake and ware yield to assess the relative effect of conventional band P rate and starter band P rate. This regression method differentiates between the effects of conventional band P and starter band P used in the factorial treatment design. Log transformation of the data did not improve the correlations.

2.1.2 Results

Petiole nutrient analysis revealed that the conventionally banded P had a greater effect on nutrient levels than the starter band P (Table 2-3). Petiole weight was significantly increased by higher rates of conventionally banded P and by the starter band treatments. In general, petiole concentrations of Al, Fe, Mg and Zn were reduced by higher rates of conventionally banded P, while petiole S and K were increased. Petiole Mg concentration decreased with higher rates of starter P while Mn concentrations increased. The MAP used for the starter band creates acidic conditions in the soil surrounding the fertiliser (Moody *et al.,* 1995b), which may have dissolved soil Mn. Since Mn is more mobile than Al or Fe in the soil (Moody *et al.,* 1995b), and also more mobile in plants (White *et al.,* 1970), it tends to concentrate in leaf tissue; whereas the Al and Fe dissolved by acidic fertilisers remain in or close to the root due to precipitation with phosphorus (Lindsay and Stephenson, 1959b). Chapman *et al.* (1992) also observed increased petiole Mn and decreased petiole Mg, in response to K application. Petiole Mn was not affect by conventionally banded P. Interactions were tested for by two way ANOVA. There were no significant interactions between starter and conventional band fertiliser rates.

Table 2-3. Main effects of conventionally banded and starter phosphorus treatments on petiole weight and nutrient analysis, (combined Forthside and Paloona 1998 data).

Phosphorus rate (kg ha^{-1})	petiole weight (mg)	P (%)	S (%)	Ca (%)	K (%)	Mg (%)	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
Conventional band									
0	85	0.24	0.25	0.82	10.5	0.45	433	271	65
30	105	0.31	0.26	0.77	10.9	0.42	386	274	69
60	113	0.32	0.26	0.79	11.0	0.42	334	267	64
120	120	0.35	0.26	0.79	11.1	0.40	326	255	61
240	123	0.42	0.26	0.81	11.0	0.42	323	262	60
F prob	<.001	<.001	0.005	NS	<.001	<.001	<.001	NS	<.001
Starter band									
0	102	0.32	0.26	0.80	10.9	0.44	367	257	64
10	111	0.32	0.26	0.81	11.0	0.42	371	265	65
20	110	0.32	0.25	0.79	10.8	0.42	342	260	61
40	111	0.33	0.26	0.79	10.8	0.41	371	279	64
80	113	0.34	0.26	0.78	10.8	0.40	352	270	65
F prob	0.002	0.019	NS	NS	NS	0.003	NS	0.023	NS
l.s.d.	4.04	0.016	0.009		0.18	0.021	53.5	14.34	4.318

There were no significant Starter x Conventional band interactions. l.s.d. applies to both main and starter means.

There were no significant effects of starter fertilisers on tuber yield or size grades other than an increase in the yield of oversize (>850 g) and reject tubers(Table 2-4). However, since the number of tubers in both of these categories was low and the larger tubers tended to contain more defects, there is greater potential for classing error to affect these results. When the reject and oversize tuber categories were combined, (neither of these categories are accepted in the ware yield), there was no effect of either starter or conventionally banded P.

Higher rates of conventionally banded P increased the yield of small tubers (<75 g and 75-250 g), caused no changes in mid-size tubers (250-450 g and 450-850 g), and decreased the yield of larger tubers (Table 2-4). The majority of the yield increase came in the 75-250 g size range and equated to an increase of 16% in total yield and 18% in ware yield at the highest rate of 240 P kg ha^{-1}.

Table 2-4. Main effects of conventionally banded and starter phosphorus treatments on tuber size grades, total and ware yields (t ha^{-1}) (combined Forthside and Paloona 1998 data).

Phosphorus rate (kg ha^{-1})	<75 (g)	75-250 (g)	250-450 (g)	450-850 (g)	>850 (g)	Reject yield	Ware yield	Total yield
Conventional band								
0	0.79	18.9	20.7	8.31	1.38	6.48	49.3	56.6
30	1.09	23.7	21.2	6.00	1.48	6.26	52.3	59.6
60	1.21	25.1	22.0	6.14	1.05	6.75	54.2	62.1
120	1.35	28.3	22.6	6.85	0.44	5.71	58.2	65.2
240	1.34	26.9	22.9	7.55	0.77	6.16	58.1	65.7
F prob	<.001	<.001	NS	NS	0.032	NS	<.001	<.001
Starter band								
0	1.03	23.4	22.9	7.21	1.44	4.98	54.9	60.9
10	1.17	25.3	19.7	6.79	0.41	7.90	52.2	61.3
20	1.24	26.1	22.2	6.35	1.46	5.89	56.1	63.2
40	1.17	24.4	22.2	7.10	1.00	6.51	54.7	62.4
80	1.17	23.6	22.4	7.40	0.81	6.10	54.2	61.5
F prob	NS[A]	NS	0.056	NS	0.025	0.011	NS	NS
l.s.d.	0.23	2.5	2.3		0.72	1.62	3.8	4.0

[A]Not significant (F prob>0.05). There were no significant Starter x Conventional band interactions. l.s.d. applies to both main and starter means.

Tuber composition was much less affected than petioles by the starter or conventionally banded fertiliser treatments (Table 2-5). There was a marginal increase in tuber Cd, on a fresh weight basis, due to the highest rate of conventionally banded P. However, this was still well below the maximum level (Cd 0.1 mg kg^{-1} fresh weight) set by the Australia New Zealand Food Authority. Tuber P was significantly increased by higher rates of conventionally banded P, with a corresponding lower, but significant, increase attributed to starter band P. Specific gravity was slightly lower in the control, zero P, compared those with 30 kg P ha^{-1} or more of conventionally banded P. Starter treatments had no effect on specific gravity.

Starter P appears to have given a comparable response to conventionally banded P during the early growth of the crop. However, multiple linear regressions of the response of petiole P uptake to both conventional band and starter band rate (Table 2-6) revealed that the ratio of starter P response to conventionally banded P response was 0.54. This indicates that the uptake efficiency of P applied to the starter band was only 54% that of an equivalent amount of P applied in the conventional banding position.

Table 2-5. Main effects of conventionally banded and starter phosphorus treatments on tuber P%, Cd and specific gravity at Forthside 1998 only.

Phosphorus rate (kg ha^{-1})	Tuber P (%)	Tuber Cd (mg kg^{-1})	Specific gravity
Conventional band			
0	0.155	0.018	1.088
30	0.155	0.018	1.091
60	0.153	0.015	1.093
120	0.171	0.018	1.091
240	0.196	0.024	1.091
FProb	<0.001	0.039	0.014
Starter band			
0	0.162	0.019	1.090
10	0.168	0.021	1.090
20	0.157	0.016	1.091
40	0.172	0.016	1.090
80	0.171	0.020	1.092
F prob	0.022	NS	NS
l.s.d.	0.010	0.006	0.003

When the regression was restricted to conventionally banded rates of 0-120 kg P ha^{-1} and compared with starter rates of 0-80 kg P ha^{-1}, the correlation was still moderate ($R^2 = 0.64$) and the corresponding ratio was 0.40. Because of the non-linear relationship between P application rate and yield, the inclusion of the highest P rate from the conventional banded P treatment (240 kg P ha^{-1}) should reduce the comparative difference.

Table 2-6. Multiple linear regressions of petiole P uptake and ware tuber yield against both conventional and starter rates of P.

	Petiole P uptake		Petiole P uptake		Ware tuber yield	
Band position	Conventional	Starter	Conventional	Starter	conventional	Starter
P rates	0-240	0-80	0-120	0-80	0-240	0-80
Slope (X1, X2)	$7.2x10^{-4}$	$3.9x10^{-4}$	$1.1x10^{-3}$	$4.4x10^{-4}$	$2.9x10^{-2}$	$1.6x10^{-2}$
F prob	<.001	<.001	<.001	<.001	<.001	0.321
Ratio	0.54		0.40		0.55	
R^2	0.72		0.64		0.14	

Slope = Δ Petiole P/ Δ P rate.

Linear regressions of main and starter rate of phosphorus on ware tuber yield produced a poor correlation, $R^2 = 0.14$. There was a significant positive effect of the main rate but no effect of starter rate (Table 2-6). See Table 4-11 for an analysis of conventionally banded P rates on tuber yields from all trial sites and years.

2.2 *The early root growth of field and pot grown potatoes*

The position of roots, particularly during the early growth periods, indicate regions where close placed fertilisers would be most effective. Potato root systems were excavated and observed throughout the field and pot trials. The root growth of mature field grown potato plants are described in Section 4.6 p 126. Intermediate root growth from a glasshouse experiment is described in Section 4.5 p 117. Results relating to the early root growth over the first five weeks are presented here.

2.2.1 Methods

Two methods were used to obtain images of potato roots during the early growth stages. In the first method one to four week old plants from both field trial sites used in 1998 were excavated to expose the root systems. Slides were taken of the exposed plants and hand drawn line pictures were made from the projected images. In the second method the roots of an entire potato plant grown in a glasshouse experiment were washed and then supported upright in a water filled tank. The roots were then digitally separated by the method described in Section 4.5.1 p 118.

The influence of flotation on root architecture was tested by superimposing images of upright and inverted roots (Figure 2-2) and axially rotated roots 180° apart. Inverting the root system (Figure 2-3a, blue image) made only minor changes to the pattern of root architecture compared to the upright root (red image). Rotating the roots system in the axial plane caused a large change in the root architecture (Figure 2-3b).

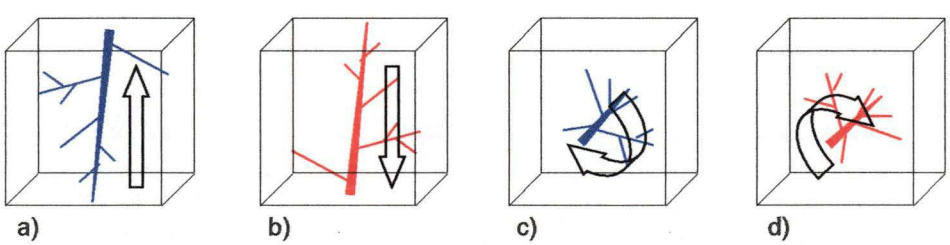


Figure 2-2. Root orientation, a) upright b) inverted c) axia l rotation left d) axial rotation right.

The roots are more susceptible to radial deflection than vertical deflection. During growth the roots are experiencing and reacting to gravity in the vertical plane but have no forces in the axial plane. Additional strengthening of the roots may occur in

the vertical plane as a reaction against gravity. The flotation tank appears a valid method for obtaining images of potato root architecture provided the roots are held in the original orientation. Differences in root strength and root buoyancies may affect the application of tank flotation to other plant species.

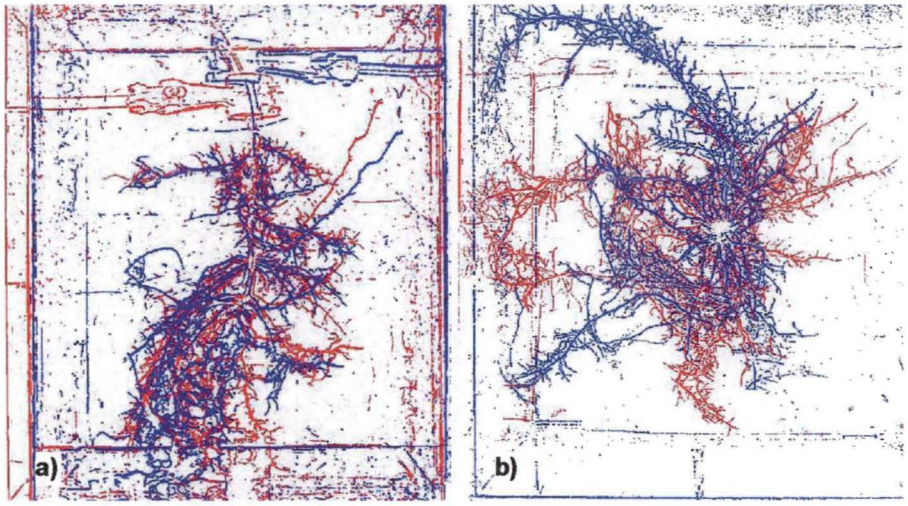


Figure 2-3. Effect of a) vertical and b) axial orientation on root flotation. Tank measures 250 mm wide x 300 mm deep

2.2.2 Results

The roots of Russet Burbank potatoes first emerge from a cluster of nodes at the base of the shoot (Figure 2-4). These roots emerge radially around the base of the potato (Figure 2-5 a, b) and tend to grow in the interface between the tuber and the soil. On older plants these roots continue to grow down at about a 45° angle (Figure 2-5 c, d).

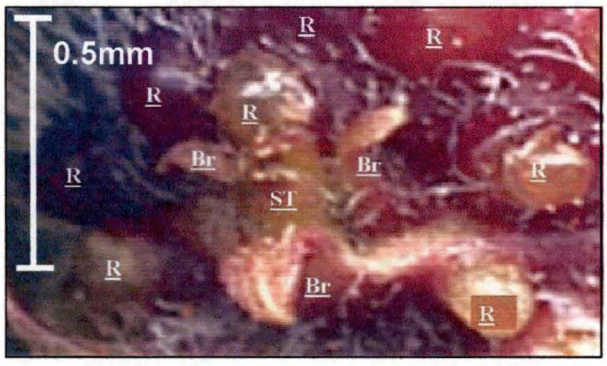


Figure 2-4. Root initial development on a potato node. Root initials R, stolon/stem, ST and bracts Br. From sprouted shoot used in the laboratory trial of liquid starter phosphorus at soil moisture above field capacity.

Younger roots emerge from higher nodes of the stem and grow progressively more horizontally so that the last roots to emerge, just below the ground surface, are nearly parallel with the ground surface (Figure 2-5 e, f). Secondary and higher order roots develop rapidly after about four weeks.

Tuber orientation plays an important role in the positioning of roots in relation to the seed tuber. Shoots emerging from the underside of the seed tuber develop a root system originating at a lower position (Figure 2-5 c). In this case, the roots grow down into the soil below the tuber and are likely to encounter the conventionally banded fertiliser sooner than shoots emerging from the upper side of tubers.

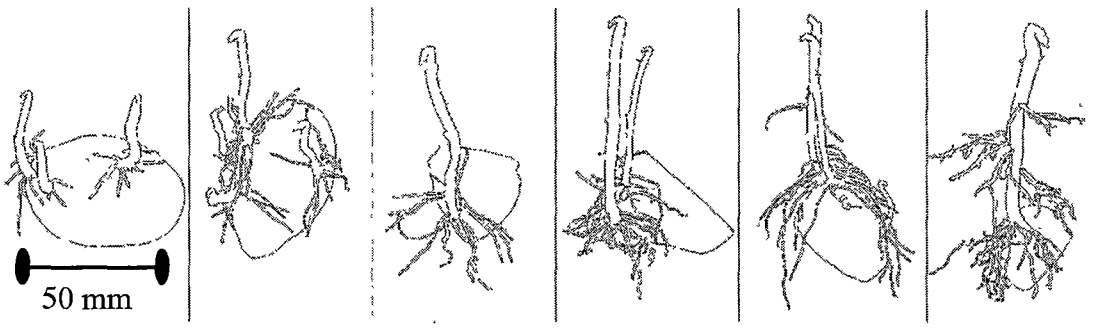


Figure 2-5. Development of potato roots over the first month of growth in the field.

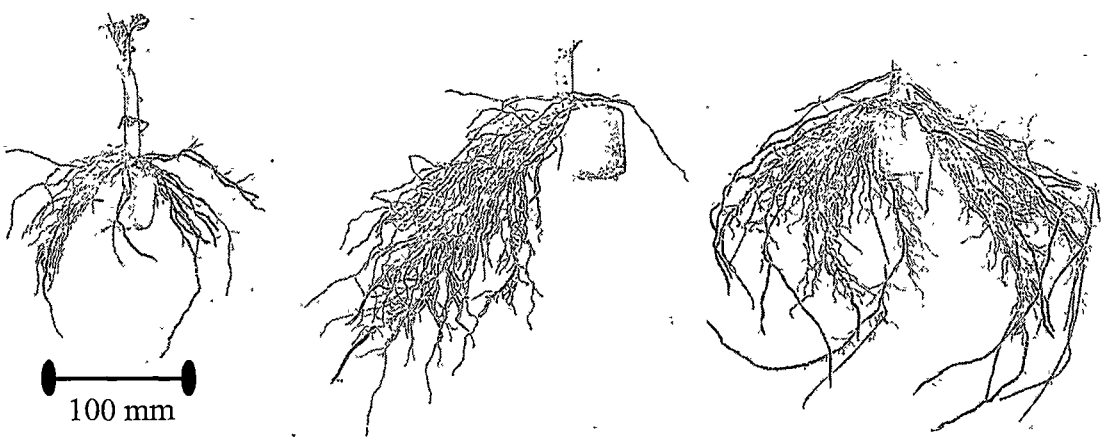


Figure 2-6. Variation in potato root growth at three weeks of pot grown potatoes.

By day 21 secondary roots are emerging from the basal half of nodal roots, but not the distal half (Figure 2-6). After three weeks of growth the general pattern of root growth resembles an inverted cone with the apex at the base of the stem (Figure 2-6). However, there may be quite pronounced inequalities in root distribution, such as

where the roots are concentrated on one side only. Older root systems may develop distinct lobes of roots centred around the arrangement of primary roots.

During the early growth stages, root distribution is confined to a conical region of soil with the apex of the cone centred over the top of the seed tuber. Placing a starter fertiliser above the sett has a low chance of interception by the roots. Fertiliser placed with the sett and below and beside the sett is more likely to be intercepted during the initial growth stages. The first images (Figure 2-5) were obtained by the slide tracing method, the second set (Figure 2-6) by the method of digital separation of floating roots.

2.3 Discussion

The initial development of the root system of potatoes is patchy and many regions of soil may remain untouched by roots. Roots systems that develop from shoots on the upper side of tubers have a greater distance to reach the conventionally banded fertiliser and are more likely to suffer from P deficiency. Those that originate from the under side of setts have a shorter distance to reach the conventionally placed fertiliser. The best position for starter P appears to be in the soil directly above or around the seed tuber (Figure 2-5). This position will provide the best possibility that the plants most in need of phosphorus can encounter the starter P band.

Observations of root growth were made throughout the field trial. The placement of the starter fertiliser with the sett provides an appropriate location for the fertiliser to be intercepted by the emerging roots. However, on many occasions the soil appeared drier in the region around the starter fertiliser than in regions further below the seed where the conventionally banded fertiliser had been applied. It is possible that soil moisture levels were rapidly reduced by the large concentrations of roots in the hilled soil. Lower soil depths maintain higher soil moisture levels which can improve P uptake (Holliday and Draycott, 1968). Without adequate moisture P uptake may have been impeded from the hilled regions (Baerug and Steenberg, 1971). More effective P uptake would be likely from the conventional banding position if more favourable moisture levels were present in the subsoil below the band.

Significant responses in petiole phosphorus content and petiole weight were obtained to starter phosphorus during the early tuberisation stages (Table 2-3 p 45). There were, however, no significant effects of starter P on the final yield (Table 2-4 p 46). The increases in petiole P% and petiole weight were no more than those which could be obtained by an equivalent amount of P applied in the conventional banding location (Table 2-6 p 47). There was only a marginal increase in tuber P concentration due to starter P compared to a 26% increase in tuber P form the highest conventional band rate (Table 2-5 p 47). Accordingly, the responses in petiole P to starter P offer no improvement to P use since no reduction in the overall rate of applied P occurs. There was no evidence of a response to starter P in the final tuber yield and only a small increase in tuber P.

Robertson *et al.* (1954) postulated that the combined effects of lower moisture levels and reduced active root growth in the zone around corn seed reduced the uptake of drill applied starter P later in the season. It is possible a similar effect occurs in potatoes, that may be further exacerbated by the growth of tubers in and around the region where starter fertilisers have been placed. Starter P may have initially been readily available to the crop, but lower or fluctuating moisture levels in the hilled soil may contribute to a reduction in the subsequent availability of P.

3 Liquid starter phosphorus

The previous field trial (Table 2-3, Table 2-4) showed that while responses in petiole P% and size could be obtained from starter P, this did not culminate in an increase in tuber yield. There may be problems with the later availability of granular starter P to the plants. Young plants have only limited reserves of phosphorus (Asher and Loneragan, 1967) and a small root system with which to acquire soil P. Unless there is a ready supply of P in the nearby soil, P deficiency may quickly develop (Costigan and Locascio, 1982). The most readily available form to supply fertilisers is as a dissolved liquid that can be immediately acquired by the emerging root system (Stone, 1998). Granular fertilisers must first be dissolved by moisture in the soil, or subsequent irrigation, before they can become available for plant uptake (Lindsay and Stephenson, 1959b).

When potato seed tubers are soaked in low strength liquid fertiliser solutions some of the nutrients are absorbed through the skin of the tuber. A component of the P absorbed in this way is available to the plant and can substitute for some of the soil applied P (Sharma *et al.,* 1977). By applying liquid starter solution containing P to the soil surrounding seed tubers it may be possible to supply P to the tuber before the roots emerge. The remainder of the starter solution, being in a dissolved and hence readily available form, could then be acquired easily by the plant once root growth commences. However, dissolved phosphorus reacts quickly in the soil and is rapidly fixed by soil colloids (Moody *et al.*, 1995b). When granular fertilisers are used, only some of the P is dissolved each time the soil is moistened, enabling P to be supplied over a longer time to the crop (Lindsay and Stephenson, 1959b). Granular fertilisers have a lower surface area in contact with the soil than occurs from liquid fertilisers, which helps to further reduce the fixation of P (Costigan, 1987). Granular P may be a better source of P for the crop during later growth stages.

A balance is therefore required between P supplied in an immediate liquid form, available over a period of days to weeks, and that applied in longer term granular forms, supplying P over weeks to months. The quantity of liquid starter P applied needs to be sufficient to promote early growth but not be so great that a large

quantity remains unused and is lost by subsequent P fixation. Since the fertiliser in granular form has a higher efficiency, applying only a small quantity of P in liquid form could alleviate an early period of P deficiency while contributing little to the overall P application.

3.1 Laboratory trial of liquid starter phosphorus at soil moisture above field capacity

Liquid fertiliser solutions have been effective at improving the early vigour of some crops (Costigan, 1984; Stone, 1998). Sharma *et al.* (1977) have shown that potato tubers can absorb nutrients directly from nutrient solutions before root growth commences. Liquid nutrient solutions applied directly to the seed potatoes may be an effective means of supplying nutrition during the early stages of crop growth. However, fertilisers placed close to emerging plants can have deleterious effects on initial root and shoot growth (Moody *et al.,* 1995b; Chu *et al.*, 1984; Zhang and Rengel, 2000). Appropriate fertiliser rates and formulations need to be identified that will promote early growth without damaging the plants. These experiments comprise a set of studies covering the effects of liquid starter fertilisers on shoot and root growth of sprouted potato shoots under soil moisture conditions above field capacity.

3.1.1 Methods

The growth of potato shoots and roots and soil solution composition were measured in ferrosol soil treated with two liquid starter fertiliser forms;

1) mono-ammonium phosphate (MAP), and

2) phosphorus acid (PA) with and without calcium nitrate (CN).

Liquid starter fertilisers were applied at the rate of 0.375 ml per gram of air dry soil in all experiments to give a moisture content slightly higher than field capacity. This is about equivalent to the air entry point for the inter aggregate pores (Tamari, 1994) and creates conditions of high moisture and aeration. Ferrosol soil obtained from the Forthside Vegetable Research Station was used for all experiments.

3.1.1.1 Mono-ammonium phosphate starter liquid

Liquid mono-ammonium phosphate MAP solutions of 0, 100, 200, 400, 800, 1600 mmol P were applied to either 80 g of soil in 120 ml vials or 500 g of soil in 500 ml

aluminium trays. Soil solution was extracted from soil in the 120 ml vials, while root growth was measured from plants grown in 500 ml trays. Sprouts were initiated on tubers by storing the tubers at 20°C under fluorescent grow tubes for three to four weeks. Well-developed shoots, average fresh weight 2.5 g, were removed from the tubers and placed on the dry soil just prior to the application of liquid treatments. The plants were grown for seven days under fluorescent grow tubes at 20 °C.

Soil solution was extracted by centrifuging 100 g of soil in two standard 50 ml centrifuge tubes. The supernatant was collected from the top of the soil pellet. Soil solution was extracted on days two, four, nine, and 27. Soil solution EC and pH were measured immediately after extraction. Soil solution ion concentrations were analysed by induction coupled plasma electron spectroscopy (ICPES). Nitrate nitrogen was measured separately by reduction with hydrazine sulphate followed by colour reaction with N-1 napthylethylendiamine at 550ηm. Soil solution ion activities were estimated by Geochem PC® software. A correction was applied to adjust the Al and Fe ion concentrations to account for suspended soil in the soil solution extracts since lanthanum chloride, recommended by Moody (1995a) had not been applied. This correction was based on the observation that soil solution Fe was chiefly derived from suspended soil, see Appendix I. Soil solution Fe could be used to identify samples contaminated with suspended soil and the concentrations of Al and Fe were adjusted accordingly. The calcium activity ratio (CAR) was calculated by dividing the calcium activity by the sum of the activities of all other cations including calcium (Section 1.2.3.4 p 11).

Root length was measured by estimating the length of each primary root to the nearest 10 mm increment. When secondary roots were present, the proportion of primary root with secondary root growth (S), the maximum secondary root length (Lmax) and the density of secondary roots along the primary root (D) were measured and used to give an estimate of total secondary root length. Secondary root length =1/2 (Lmax x D x S x primary root length). Results were analysed by two way ANOVA of MAP rate against time.

3.1.1.2 Phosphorus acid and calcium nitrate starter liquid

A factorial combination of phosphorus acid (PA) 0, 35, 100, 320 mmol P and calcium nitrate (CN) 0, 0.4, 1.1, 3.3, 10, 30 mmol Ca in four replicates was used to evaluate the optimum rate of P that could be used in liquid starter solutions and whether additional Ca was required to alleviate Ca deficiency. Potato shoots were grown directly in the 120 ml vials from which the soil solution was obtained. Two additional replicates, without plants, were included to evaluate the effects of plant growth on the soil solution concentrations. On day seven the sprout shoots were removed and their nutrient content analysed by ICPES. Soil solution was also extracted on day seven. Plant growth conditions and soil solution extraction and analysis were the same as for the liquid MAP experiment (Section 3.1.1.1 p 54). Soil solution ammonium was measured by a modified method 7A1 of Rayment and Higginson (1992), where ammonium was determined by solution electrical conductivity rather than titration. There were no significant differences in soil solution concentrations from treatments with plants compared to those without. Results were analysed by a factorial ANOVA of PA rate against CA rate.

3.1.2 Results

3.1.2.1 Mono-ammonium phosphate starter liquid

Total plant root length reached a maximum with the 100 mmol P MAP solution. Root length declined with higher strength solutions (Table 3-1). There was a significant decrease in root length occurring between Calcium Activity Ratio (CAR) of 0.13 and 0.05 predicted by Geochem®. However, since soil solution salinity also increased with the rate of MAP, it is not possible to discriminate between the effects of CAR and EC from the present results. Moody *et al.* (1995a) found that a CAR of 0.05 and an EC of 4.1 dS m^{-1} were the critical levels for a 10% reduction in relative root growth of soybeans.

Soil solution acidity was unlikely to affect growth, since the pH remained above 5.5. Significant levels of Al^{3+} or Mn^{2+} are likely to be released only when the pH falls below 5.5 and a pH below 4 is required for H^{+} injury (Moody *et al.*, 1995b). The activities of Al^{3+} and Mn^{2+} were unlikely to be high enough to cause a reduction in root growth. The pH is, however, decreased by the addition of MAP; and since the

equilibrium pH of MAP in saturated solution is around 3.4-4.0 (Moody *et al.*, 1995b; Huffman and Taylor, 1963), there is the possibility of acidity injury when high rates of MAP are applied. Ammonia activity was increased initially (Table 3-1); however, this was followed by only small increases following the addition of more MAP due to the acidifying affect of MAP. The ammonia levels remained well below the solution ammonium (NH^{4+}) levels. The vaporisation of ammonia is reduced at lower pH (Findenegg, 1987), hence ammonia activity from an acidifying fertiliser like MAP is less likely to reach levels that affect root growth.

Table 3-1. Soil solution ion activities as –log of molar concentrations, pH, EC, CAR and root length nine days after the addition of MAP (0 – 1600 mmol P).

MAP (mmol l^{-1})	PO_4^{3-}	Ca^{2+}	Al^{3+}	Fe^{3+}	Mn^{2+}	SO_4^-	NH^{4+}	NH_3	pH	EC (dS m^{-1})	CAR	Root (mm)
0	5.62	3.30	8.22	12.9	6.02	3.92	ND*	ND	6.75	0.3	0.375	55
100	3.62	3.21	6.73	12.1	5.91	3.30	2.48	4.76	6.77	1.2	0.127	168
200	2.94	3.17	6.89	11.2	5.96	3.11	1.90	4.71	6.24	2.2	0.046	96
400	2.04	3.26	7.18	11.5	5.79	2.86	1.57	4.63	6.02	3.4	0.020	23
800	1.45	3.43	7.61	11.7	4.97	2.69	1.20	4.22	6.08	6.5	0.006	0
1600	0.89	3.71	8.04	12.3	4.79	2.68	0.75	4.03	5.85	12.2	0.001	0
F prob	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.002	<.001	<.001	<.001	0.004
l.s.d.	0.43	0.18	0.64	0.47	0.31	0.07	0.41	0.42	0.14	0.5	0.085	67

* Not detectable

Soil solution phosphate concentration decreased the longer the MAP reacted with the soil (Figure 3-1). Soil solution P concentrations from the low P rate treatments, P<400 mmol, were reduced to concentrations close to the unamended control levels by day 27. Nearly all the P within the soil solution had diffused to and subsequently been sorbed by the soil over a three to four week period. Substantial amounts of P remained in the soil solution after 27 days from the higher P rate treatments, P>400 mmol.

The high rates of applied P saturate the P sorption sites on the soil minerals (Agbenin and Tiessen, 1995). By concentrating the P in high strength solutions more P can be kept in a chemically available, unsorbed, form. Such high rates of P could maintain adequate to high concentrations of P for several weeks after the addition of liquid MAP to soil. This is in agreement with other findings (Barber, 1980) that by increasing the fertiliser P concentration the period over which P is available for plant uptake can be extended. A balance needs to reached between the deleterious effects

of stronger phosphorus solutions on root growth and benefits from reduced P fixation from stronger phosphorus solutions.

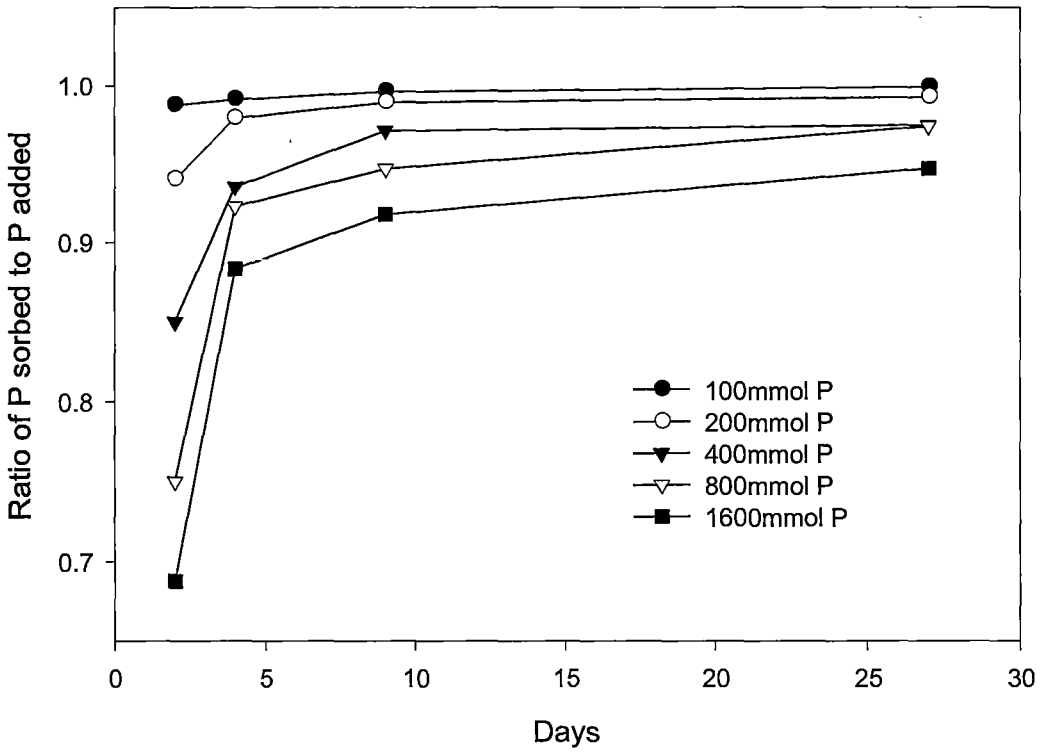


Figure 3-1. Ratio of phosphorus sorbed to phosphorus added (100 – 1600 mmol P) in soil solution over a 27 day period.

3.1.2.2 Phosphorus acid and calcium nitrate starter liquid

The root length of potato sprouts was increased only by the lowest rate of P (35 mmol). The highest rate of P (320 mmol) significantly reduced potato root length below that of the 35 mmol P treatment and tended to reduce the root length below the control treatment (Figure 3-2). Since the addition of calcium salts had no significant effect on root length and the calcium activity ratio (CAR) for all treatments are above 0.10 (Table 3-2), calcium deficiency is unlikely to be the cause of the root length decline. The most saline treatment, 320 mmol P with $Ca(NO_3)_2$ 58 mmol l^{-1}, had an EC of 4.75 dS m^{-1} and hence was close to the threshold for salinity induced root inhibition of soy bean roots (Moody *et al.*, 1995a). Evidence suggests that potatoes are sensitive to salinity at levels similar to or higher than soybeans (Heuer and Nadler, 1995; Kotuby-Amacher *et al.*, 2000). However, there was no significant effect of $Ca(NO_3)_2$ rate alone on root length even though salinities ranged from 0 to

>4 dS m^{-1} (Table 3-2). Hence, an effect of salinity on potato root length was not detected within the range of salinities used.

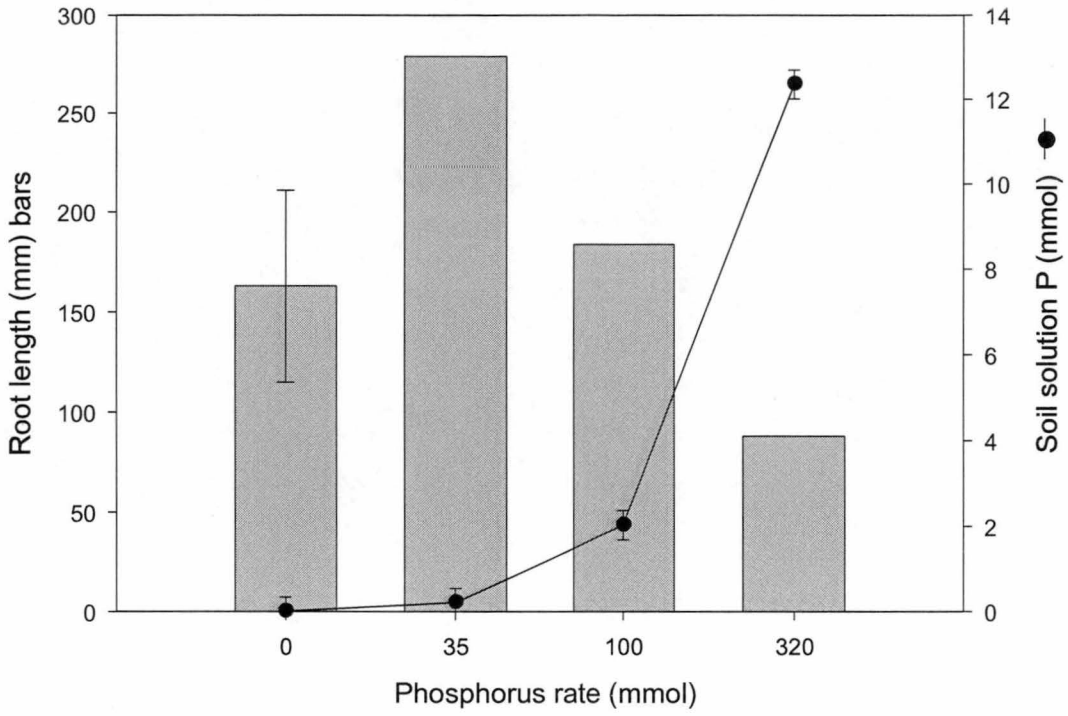


Figure 3-2. Potato shoot root length and soil solution P concentration after applications of H_3PO_3 (0 - 320 mmol P) and $Ca(NO_3)_2$ (0 - 30 mmol Ca) to a ferrosol. Root length (bar with l.s.d.) soil solution P (line).

Sorption of P by the soil reduced the 35 mmol starter solution to soil solution P concentrations of around 0.3 mmol P (Figure 3-2). Moody *et al.* (1995b) found root inhibition of soybeans occurred when soil solution P concentrations entered the range of 1.0-10 mmol P. Hydroponically grown tomatoes develop symptoms of P toxicity at a solution strength of 5 mmol P (Penalosa *et al.*, 1989). In this experiment a significant reduction in root growth occurred once the soil solution strength exceeded around 10-15 mmol P.

Soil solution pH was reduced by the addition of either $Ca(NO_3)_2$ or H_3PO_3. While the pH was not low enough to cause H^+ toxicity, it was sufficiently low in some treatments to cause Al^{3+} and Mn^{2+} dissolution at levels that may be toxic to root growth (Moody *et al.*, 1995c). Both aluminium and manganese activities were

significantly increased by the lower pH (Figure 3-3). A large rise in Al^{3+} activity occurred at pHs below a threshold value of around pH 4.8 with a similar increase in Mn^{2+} activity at a slightly higher threshold of around pH 4.9.

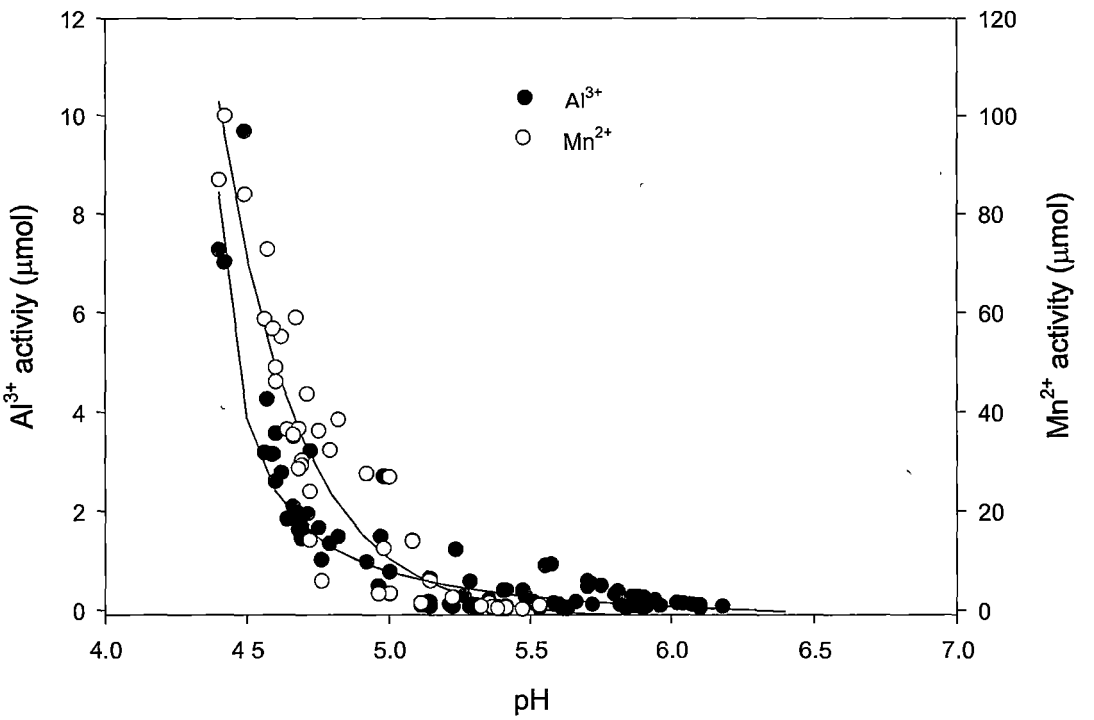


Figure 3-3. Relationship between soil solution pH, Al^{3+} and Mn^{2+} activities from ferrosol soil after factorial additions of H_3PO_3 (0 - 320 mmol P) and $Ca(NO_3)_2$ (0 - 30 mmol) solutions. Activity of Al^{3+} > 1.6 at pH 5.4 and activity of Mn^{2+}>70 at pH 4.5.

Most soil solution ion activities were affected by both $Ca(NO_3)_2$ and H_3PO_3 additions (Table 3-2). Activities of all soil solution cations were increased at higher rates of $Ca(NO_3)_2$ due to displacement by Ca^{2+}. The activities of anions PO_4^{3-} and SO_4^{2-} were decreased when more $Ca(NO_3)_2$ was added due to precipitation and ion pair formation with calcium (Lindsay and Stephenson, 1959a). The CAR initially does not change with increasing additions of $Ca(NO_3)_2$, even though Ca^{2+} activity is increasing. This effect was probably due to buffering by cation displacement off the soil colloids. $Ca(NO_3)_2$ rates of 19 mmol or more decreased CAR due to an increased dissolution of Mn, Fe and Al from the more acidic soil conditions (Table 3-2). The CAR is increased by higher rates of $H_3P_rO_3$ due to the complexation of Al and Fe ions with phosphate and the low stability of calcium phosphates in acidic conditions (Lindsay *et al.*, 1959). However, CAR does not reach values in any

treatments that are limiting to the root growth of soybeans, (CAR <0.05). It is unlikely that CAR significantly influenced the growth of roots when phosphorus acid starter solutions were used.

Table 3-2. Main effect means of soil solution ion activities as –log of molar concentrations, pH, EC, CAR and root length seven days after the application of H_3PO_3 (0 - 320 mmol P) and $Ca(NO_3)_2$ (0 - 30 mmol).

$Ca(NO_3)_2$ (mmol l^{-1})	PO_4^{3-}	Ca^{2+}	Al^{3+}	Fe^{3+}	Mn^{2+}	SO_4^-	pH	EC (dS m^{-1})	CAR	Root length (mm)
0	3.01	3.23	6.44	11.3	7.69	3.06	5.51	0.73	0.18	148
0.7	2.99	3.28	6.18	11.0	7.73	3.03	5.49	0.73	0.20	144
2.1	3.03	3.24	6.28	11.2	7.53	3.08	5.45	0.93	0.19	216
6.4	3.11	3.16	6.34	11.3	7.33	3.16	5.34	1.23	0.19	174
19.3	3.17	3.13	6.25	11.3	6.95	3.24	5.19	2.15	0.15	212
58	3.30	3.02	5.94	11.0	6.50	3.23	4.98	4.43	0.14	179
F prob	***	***	*	**	***	***	***	***	***	NS
l.s.d.	0.07	0.04	0.29	0.20	0.43	0.02	0.07	0.05	0.02	
H_3PO_3 (mmol l^{-1})										
0	4.00	3.31	6.18	11.2	9.00	3.49	5.79	1.44	0.17	163
35	3.77	3.30	6.38	11.0	8.83	3.16	5.62	1.51	0.15	279
100	2.72	3.17	6.68	11.3	6.96	3.00	5.23	1.64	0.18	184
320	1.92	2.92	5.71	11.2	4.37	2.88	4.66	2.20	0.20	88
F prob	***	***	***	**	***	***	***	***	***	***
l.s.d	0.06	0.03	0.23	0.2	0.36	0.02	0.06	0.05	0.02	62

Level of significance * F > 0.05, ** F > 0.01, *** F > 0.001

Total plant tissue concentrations were only slightly affected by $Ca(NO_3)_2$ (Table 3-3). There was an increase in shoot Ca at the highest rate of $Ca(NO_3)_2$, possibly reflecting the increase in Ca^{2+} activity in the soil solution. Likewise, total plant P was increased by higher rates of phosphorus acid. Total plant Al reached a maximum at the lowest rate of phosphorus acid and decreased thereafter. Similar trends occurred with total plant Fe and total plant S.

Tissue Mn concentrations did not increase in response to decreasing pH. The average critical minimum concentration from a range of crops, not including potatoes, given by (Hannam and Ohki, 1988) was 16 mg kg^{-1} Mn. A tissue Mn value of around 200 mg kg^{-1} Mn is required before symptoms of Mn toxicity are expressed in potatoes and other plants (Cheng and Ouellette, 1968; Foy *et al.*, 1988). With an average value of 32 mg kg^{-1} Mn, the potato sprouts were above deficient Mn levels

but well below toxic concentrations. Mn toxicity is usually expressed in the shoot tissue since it is mobile in the xylem and tends to accumulate in the leaf tissue after transpirational loss of the xylem water (Loneragan, 1988). In young potato shoots where the transpirational flow is low, due to a low leaf area, Mn concentrations in the shoot may not reach toxic levels.

Table 3-3. Main effect means of shoot tissue dry weight and nutrient concentration seven days after the application of H_3PO_3 (0 - 320 mmol P) and $Ca(NO_3)_2$ (0 - 30 mmol).

$Ca(NO_3)_2$ (mmol l^{-1})	P (mg g^{-1})	Ca (mg g^{-1})	Al (mg g^{-1})	Fe (mg g^{-1})	Mn (mg g^{-1})	S (mg g^{-1})	Shoot DM (g)
0	4.53	12.8	1.35	0.71	0.04	3.58	0.31
0.72	4.13	13.4	1.36	0.75	0.03	3.44	0.32
2.1	4.46	14.7	1.82	1.00	0.04	3.34	0.30
6.4	4.15	13.3	1.87	1.03	0.04	3.32	0.31
19.3	4.20	14.5	1.73	0.92	0.04	3.39	0.35
58	4.28	21.2	1.82	0.98	0.04	3.41	0.29
F prob	NS	***	NS	NS	NS	NS	NS
l.s.d.		2.2					
H_3PO_3 (mmol l^{-1})							
0	4.00	14.6	1.39	0.76	0.03	3.36	0.31
35	4.08	14.6	2.30	1.16	0.04	3.52	0.35
100	4.35	15.1	2.15	1.13	0.03	3.57	0.33
320	4.74	15.6	0.79	0.55	0.03	3.21	0.27
F prob	***	NS	**	*	NS	*	*
l.s.d.	0.3		0.89	0.43		0.23	0.05

Level of significance * F > 0.05, ** F > 0.01, *** F > 0.001

Neither salinity nor CAR had a measurable effect on potato root length in this experiment. However, both Al^{3+} and Mn^{2+} activities increased in conjunction with decreasing root length and reached levels that would be sufficient to cause a reduction in root length of soybeans at pH 5.4 for Al (1.6 µmol) and pH 4.5 Mn (70 µmol) (Moody *et al.*, 1995b). Potatoes are likely to be less susceptible to acidity than soybeans. Horst and Schmohl (2001) found a 55% relative root elongation (RRE) of potatoes occurred at Al activity of 25 µmol, in comparison to soybeans where the Al activity for 55% RRE was 8 µmol (Moody *et al.*, 1995b). This is a three-fold increase in the Al activity threshold of potatoes. The correlations between Al and Mn activity and root length are low and were $R^2 = 0.28$ and $R^2 = 0.45$ respectively. More refined experimental methods to measure root growth would be required to quantify whether the reduction in root growth is due to Al or Mn. A pH

induced Al and or Mn toxicity is a likely cause for the observed reductions in root length from higher strength P solutions. There was insufficient sensitivity in the root length data from this experiment to separate the effects of Al and Mn on root growth.

3.2 Field trial of liquid starter phosphorus

The laboratory trials using liquid starter solutions at soil moisture conditions above field capacity indicated solution strengths of up to 100 mmol P could be applied without harming the roots of young potato plants. In 1999 a trial was established at Forthside Vegetable Research Station to test starter P treatments of up to 160 mmol P under field conditions. Starter solutions were applied either as spots directly over the seed or as a continuous band over the seed.

3.2.1 Methods

Liquid starter fertilisers consisting of control (no liquid) and liquid P rates of 0, 0.4, 0.8, and 2 kg P ha^{-1} were applied to plots receiving conventionally banded P of either 50 or 100 kg P ha^{-1}. Two methods of starter fertiliser application were used, either as a spot (pulsed) application of 10 ml of solution directly over the sett or as a continuously applied band of liquid at a rate of 20 ml per plant. Starter solutions used for the continuous application were diluted 1:1 with water to maintain the same starter application rate as the spot treatment. Two forms of liquid starter solutions used were:

i) MAP with finely ground gypsum.

ii) Phosphorus acid with calcium nitrate;

These starter fertiliser combinations were designed to supply a constant P:N:Ca ratio of 2:1:1.5 without adversely increasing the soil pH, which may occur when di-ammonium phosphate is used (Moody *et al.,* 1995b).

The conventionally banded fertiliser contained a uniform application of N 220 kg ha^{-1} (DAP and Urea), K 300 kg ha^{-1} (K_2SO_4) and S 130 kg ha^{-1} (K_2SO_4) that was applied through two variable rate fertiliser boxes. A further series of plots received triple super phosphate of 0, 150, 200 and 300 kg P ha^{-1} in the conventional band, from which a P response curve was obtained which were applied in duplicate. The nil starter give the conventional band 50 and 100 kg P ha^{-1}.

The liquid fertilisers were injected directly into the furrows during planting from a nozzle placed behind the planter shoe (Figure 3-4). Potato hills were formed during the planting operation. The liquid starter fertilisers were held in plastic containers and forced out through the nozzle by applying compressed air at 50-100 kPa to the containers. A tap in the outlet line could be pulsed to apply the spot starter treatments or held continuously open for the band starter treatment.

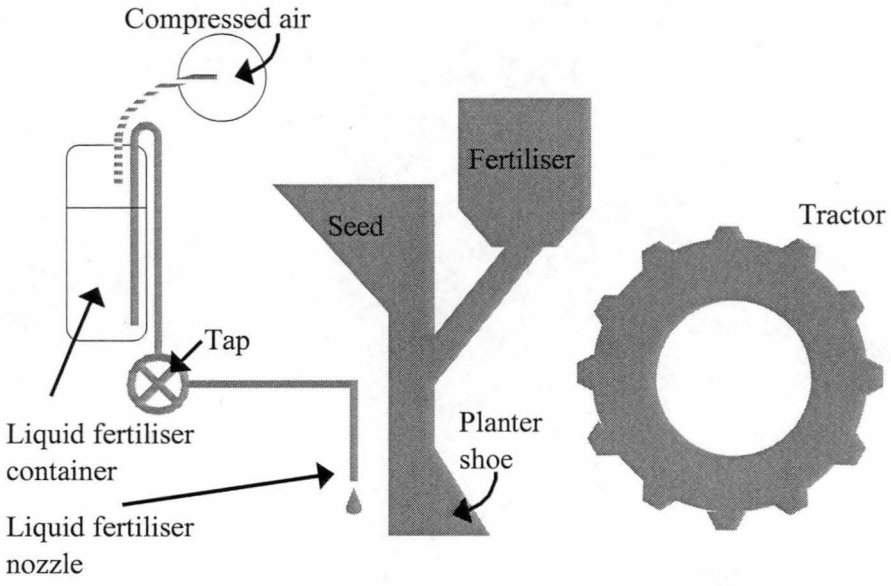


Figure 3-4. Diagram of equipment used to apply liquid starter treatments.

Crop planting, harvest and tissue sampling dates are given in (Table 2-2 p 43). The farm manager at Forthside Vegetable Research Station carried out crop husbandry. Irrigation was by travelling irrigator, with two irrigator laneways in the trial.

Crop senescence was visually scored on 17/3/00 with plants being ranked from one for a complete green canopy to five for a fully senesced canopy. Soil samples were collected from the top 5 cm of each plot, from a bulked sample of ten sub samples, during late senescence on 17/3/00. These were analysed for Colwell P and K and select samples analysed for organic carbon (Table 4-10). The distribution of irrigation water was measured by placing catch cans across the trial prior to irrigating. Soil available P (Colwell) and senescence scores were compared with irrigation and tuber yield data by bulking the plot values along each of the 26 trial rows, with six plots to each row.

A factorial design with incomplete randomisation in the starter treatment was used due to restrictions in changing between spot and band application methods along a planting row. The spot or band treatments were alternated across 26 rows. Treatments were replicated across three blocks. This experiment was a partial split plot design, whole plots comprising the row in which either spot or band treatments were applied and split plots being the starter rate. However since the whole plots were incomplete and devided across the whole block a completely randomised ANOVA was more suitable for the analysis than a split plot design. The results were analysed by ANOVA as starter P rate*P form*placement*conventional band P rate.

3.2.2 Results

There were no statistical differences between the spot or band starter P treatments. These treatments were pooled which removed the partial split plot effect, allowing analysis by completely randomised ANOVA. There were no significant effects of the pooled liquid starter fertiliser treatments on petiole nutrition, petiole weight, (Table 3-4), or tuber yield or tuber size grade.

Table 3-4. Main effect of starter liquid phosphorus rates (0 – 2 kg P ha^{-1}) on petiole weight and petiole nutrient analysis.

Starter Band P (kg ha^{-1})	Petiole weight (mg)	P (%)	S (%)	Ca (%)	Mg (%)	K (%)
0	201	0.27	0.40	1.14	0.39	6.8
0.4	206	0.26	0.40	1.14	0.39	6.5
0.8	197	0.27	0.41	1.16	0.40	6.4
2.0	196	0.27	0.40	1.19	0.40	6.3
F prob	NS	NS	NS	NS	NS	NS

There were few effects of conventionally banded P rate on petiole nutrition (Table 3-5); however, there was a strong response of petiole P to higher rates of conventionally banded P. The petiole K levels were below the optimum range of 11-12% reported by (Chapman *et al.*, 1992) and K deficiency may have limited responses to P despite the application of 300 kg K ha^{-1} as fertiliser.

Table 3-5. Main effect of conventionally banded rates of phosphorus (0 – 300 kg P ha^{-1}) on petiole weight and petiole nutrient analysis.

Conventional (P kg ha^{-1})	Petiole weight (mg)	P (%)	S (%)	Ca (%)	Mg (%	K (%)
0	195	0.26	0.40	1.27	0.45	6.1
50	196	0.28	0.40	1.11	0.38	6.9
100	206	0.27	0.41	1.17	0.40	6.7
150	188	0.30	0.41	1.09	0.38	7.1
200	230	0.35	0.41	1.04	0.37	6.9
300	191	0.35	0.43	1.16	0.39	7.2
F prob	NS	<.001	NS	0.056	NS	NS
l.s.d.		0.035		0.132		

There were no effects of starter treatments on tuber yield. Conventionally banded rates of 50 kg P ha^{-1} or more significantly increased both total and ware tuber yields (Table 3-6). The majority of this increase was accounted for in the 250-450 g size range. However, there was also a trend for the yield of 150-250 g tubers to increase with higher P rates. Reject and under sized categories were not affected by the conventionally banded P rate.

Table 3-6. Main effect of conventionally banded rates of phosphorus (0 – 300 kg P ha^{-1}) on tuber size grades, total and ware yields (t ha^{-1}) for Forthside 1999.

Conventional P (kg ha^{-1})	<75 (g)	75-150 (g)	150-250 (g)	250-450 (g)	>450 (g)	Reject yield	Total yield	Ware yield
0	1.10	8.6	17.8	15.5	3.0	0.5	46.5	44.9
50	0.94	6.5	18.5	21.6	5.6	0.6	53.8	52.2
100	1.09	7.0	20.1	22.9	3.9	0.5	55.0	53.9
150	1.44	7.5	19.5	20.3	3.8	0.7	54.1	51.2
200	1.10	5.4	23.3	24.0	2.7	0.0	56.4	55.3
300	0.96	6.9	17.4	28.0	5.8	0.1	59.1	58.0
F prob	NS	NS	0.062	<.001	NS	NS	<.001	<.001
l.s.d.			4.39	4.95			2.25	5.86

The lack of measurable responses to the liquid starter treatments was most likely due to the low absolute rates of P used in the starter solutions, the highest rate being equivalent to P 2 kg ha^{-1}. There are difficulties in handling larger volumes of starter solutions, and risks of fertiliser injury if higher strengths of P solutions are used (Moody *et al.* 1995b) and Figure 3-1. Ratio of phosphorus sorbed to phosphorus added (100 – 1600 mmol P) in soil solution over a 27 day period.. The strength of the starter P solutions was within the range that should not cause damage to emerging roots (30-160 mmol P, Table 3-2 p 61), but there may not have been sufficient total P applied for a response.

Irrigation of the trial started at about the time of crop emergence. This is earlier than would normally be required, especially since the crop was planted into already moist soil. The trial was established in a larger paddock containing other potato trials that had been planted three to four weeks earlier. These trials required irrigation and since a travelling irrigator was being used, the whole paddock was irrigated together. Normally the irrigation of potatoes is avoided until after emergence to avoid seed piece decay (Anon., 1969) and to reduce the number of tubers set (Struik and VanVoorst, 1986; Shock *et al.,* 1992). The application of irrigation shortly after planting is likely to reduce or remove altogether any response to liquid starter fertilisers (Reiners *et al.,* 2001). Hence under more normal, drier conditions a response to the starter liquids may have been obtained.

A variation in irrigation application rate occurred across the trial. The irrigation coverage in the region between the irrigator runs was quite uniform, 30-35 mm per run; however, the first ten to twelve crop rows either side of the irrigator runs received up to 50% more water. Soil available P was measured from each plot and followed a similar trend to the irrigation distribution (Figure 3-5). The increase in available P may be due to increases in organic matter mineralisation. Available phosphorus is linked to microbial pools and a moister environment may increase the microbial activity and hence the pool of available P (Sparling, 1985). The level of irrigation may be affecting the rate or timing of organic matter turnover.

The proportion of tubers larger then 450 g was moderately correlated with the senescence score (Figure 3-6). Plants that senesced late had a higher proportion of tubers >450g. The longer growing season has resulted in the continued growth of existing tubers.

The relationships between irrigation rate and Colwell P and between senescence and the proportion of tubers > 450 g were moderate, with R^2 of 0.68 and 0.69 respectively. However, the correlation between irrigation and senescence was poor, R^2=0.31. The lowest senescence scores occurred in the rows with the lowest irrigation rates, hence there was a weak effect of irrigation on the persistence and tuber size of the crop. Higher rates of irrigation may have caused nitrate leaching.

Nitrogen depletion can cause early senescence and may have contributed to observed the variation in senescence (Marschner, 1986).

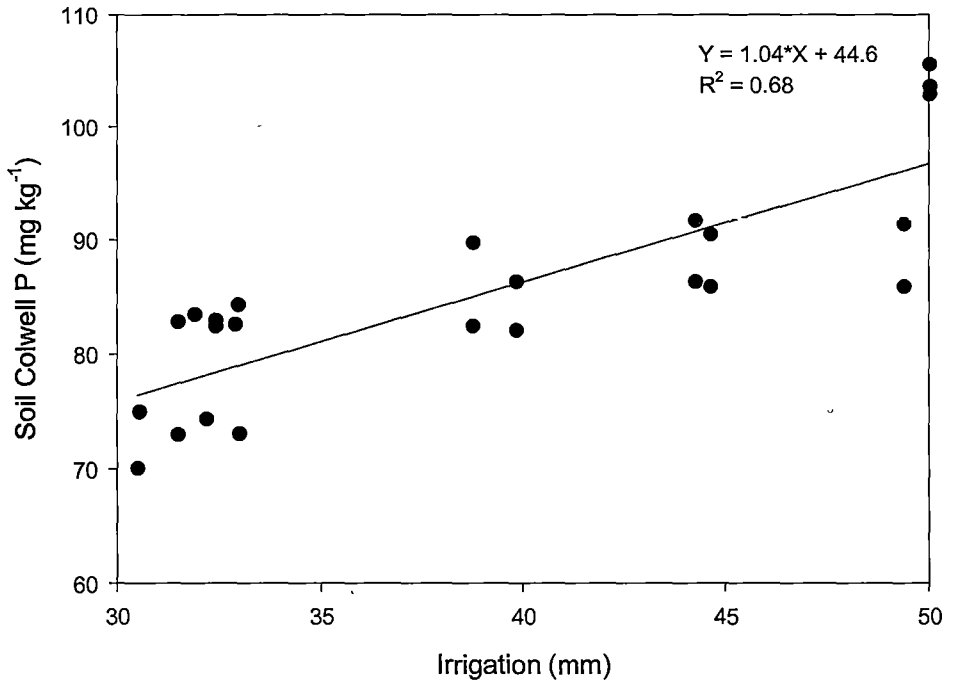


Figure 3-5. Correlation of soi l Colwell P and irrigation rate.

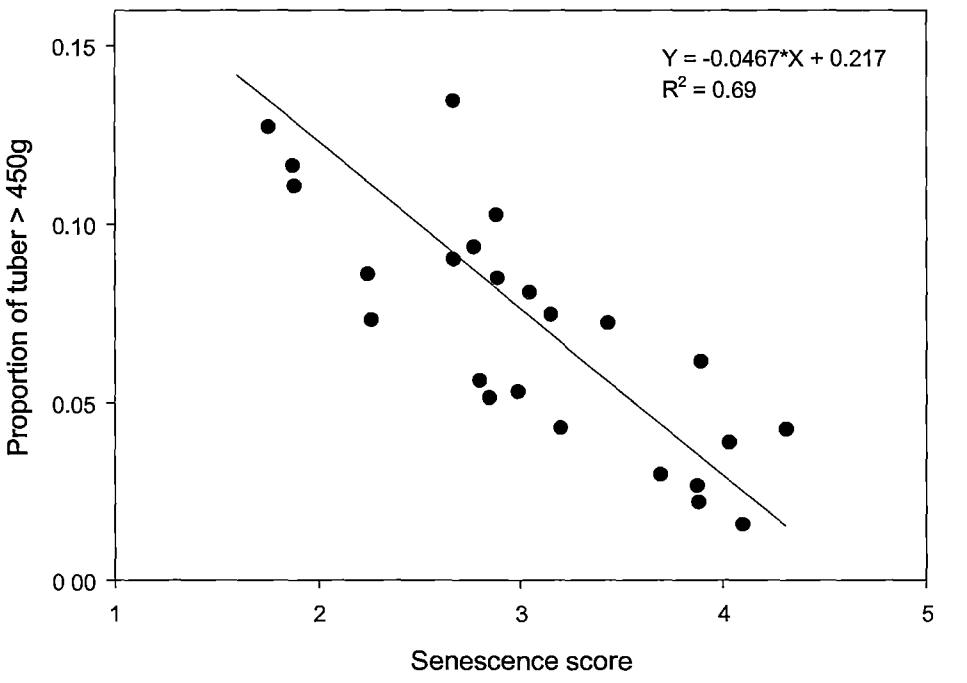


Figure 3-6. Correlation of the proportion of tubers > 450 g and senescence score.

3.3 *Glasshouse trial of liquid starter phosphorus at soil moisture below field capacity*

Two glasshouse pot trials of liquid starter P at soil moisture above field capacity were established at the same time as the liquid starter P field trial (Section 3.2 p 63). These trials were established to examine the effects of liquid starter P on the early sprout growth and emergence of potatoes in situations more closely resembling field conditions, ie soil moisture levels below field capacity, than the previous liquid P trials.

3.3.1 Methods

In the first trial, liquid MAP only was applied to seed tubers at planting, no other P fertilisers were applied. The second trial repeated the starter treatments used in the first trial but included an application of conventionally banded P to evaluate the effects of starter P in conjunction with conventionally banded fertiliser. In both trials 10 ml of liquid starter P containing MAP was applied to each plant. In the first trial the only P source was in the starter liquid. In the second trial both starter P and conventionally banded P, as a split band 50 mm below and 50 mm beside the seed, were applied. Potato plants in both experiments were grown in a 1 m x 2 m x 0.25 m tray in four rows at 100 mm spacing between plants along the row. All trials were grown in a glasshouse and in ferrosol soil collected from Forthside Vegetable Research Station.

3.3.1.1 Mono-ammonium phosphate starter liquid without conventionally banded P

Seed tubers of three physiological stages were used. They were planted either a) directly from cool storage, b) after a two week period of warm storage but in an unsprouted condition or c) after two weeks warm storage and with active sprouts. Only results from the warm storage sprouted treatment (c) are presented since the other treatments (a and b) failed to grow appreciably during the time of the trial. Starter treatments comprised liquid solutions of 400, 800, 1600 mmol P (equivalent to 5, 10, 20 kg P ha^{-1}) as mono-ammonium phosphate. The starter treatments were applied at a rate of 10 ml per plant directly over the buried seed. Three plants from each treatment were sampled on days 18, 23, 31, 39, and 44 after planting. Primary and secondary root lengths were measured (Section 3.1.1.1 p 54), and shoot nutrient

levels analysed by ICPES (Section 3.1.1.1 p 54). Results were analysed by a two way ANOVA of P rate and time.

3.3.1.2 Mono-ammonium phosphate starter liquid with conventionally banded P

Potato plants were grown from 20 g cores cut from larger seed potatoes. Each core had only one sprout and was stored before planting for two days to allow wound healing. The trial was planted on 22/9/99 and six plants from each plot were sampled on days 12, 30 and 36 after planting. The whole plants were removed and washed free of soil. Shoot and root dry weights were recorded and root length measured on the first sampling date only. Phosphorus and Calcium in the dried shoot material were analysed by ICPES (Section 3.1.1.1 p 54). The results were analysed by a two way ANOVA of P rate by time as days after planting.

Conventionally banded P of up to 100 kg ha^{-1} was applied in the standard banding position (Figure 2-1). Starter treatments comprised liquid solutions of 400, 800, 1600 mmol P (equivalent to 5, 10, 20 kg P ha^{-1}) as mono-ammonium phosphate. The starter treatments were applied at a rate of 10 ml per plant directly over the buried seed. Conventionally banded fertilisers were supplied with sufficient P to bring the total P, both starter P and conventionally banded P, to 100 kg P ha^{-1}, 200 kg N ha^{-1} and 300 kg K ha^{-1} and were placed as two bands 50 mm below and 50 mm beside the seed. The plants were watered by overhead sprinklers as required.

3.3.2 Results

3.3.2.1 Mono-ammonium phosphate starter liquid without conventionally banded P

Although there were no statistical differences between nodal root lengths, on four out of five samplings primary root growth was lowest in the control treatment (Figure 3-7). Secondary and higher order root growth only began from day 32. After day 32 there was a significant ($P = 0.02$) difference in secondary root growth between those plants receiving P solutions and the control (Figure 3-7). It is likely that by 39 days after planting, P deficiency was limiting the growth of secondary roots in the control treatment. This result indicates that the starter P solution is being effectively utilised

by the plants. However, there was no conventionally banded P for comparison so the relative benefit of the starter band cannot be assessed. Ammonium present in the starter band may also be responsible for the increased root branching seen in the starter P treatments after day 32 (Drew, 1975).

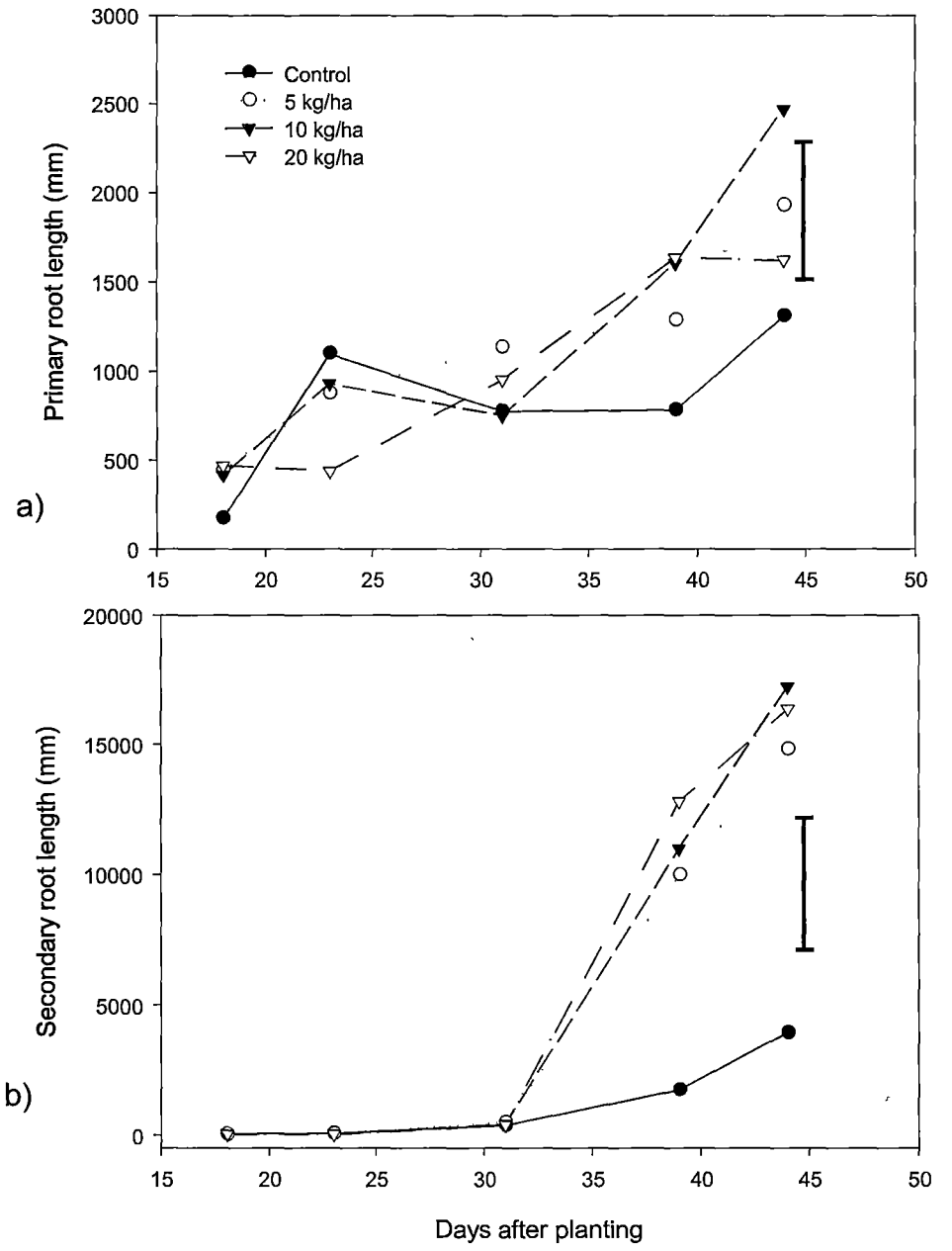


Figure 3-7. Effects of MAP starter liquid phosphorus rate on, a) primary root length, b) secondary root length. Error bars are l.s.d. at P = 0.05.

Under normal planting conditions the individual primary roots should be long enough, about 100 mm, to reach the conventionally banded fertiliser by about the time secondary root growth begins at four to five weeks. Hence, it seems unlikely that severe P deficiency can occur when conventionally placed fertiliser bands are within 50 mm of the seed.

3.3.2.2 Mono-ammonium phosphate starter liquid with conventionally banded P

The largest increase in potato shoot weight was obtained from the lowest rate of MAP, 400 mmol P. Higher rates of P reduced the shoot weight (Table 3-7). Primary root weight was increased with the 400 mmol P-starter liquids after 36 days of growth. There was, however, no significant effect of starter applied P on root weight from twelve to 30 days after planting. The phosphorus content of both the shoots and roots was increased according to the P rate. Calcium in the plant tissue remained at similar levels under the control and low P rates but was significantly reduced by the highest P application rate (P 1600 mmol).

Table 3-7. Effects of starter liquid MAP rate and time after application on shoot and root dry matter weight, phosphorus and calcium content from days twelve to 36 after planting.

MAP (mmol)	Days	Shoot weight (mg)	Shoot P (%)	Shoot Ca (%)	Root weight (mg)	Root P (%)	Root Ca (%)
0		0.67	0.38	0.56	0.12	0.27	0.67
400		0.99	0.46	0.56	0.10	0.33	0.63
800		0.63	0.49	0.56	0.11	0.38	0.52
1600		0.48	0.53	0.48	0.09	0.43	0.54
F prob		<.001	<.001	0.003	NS	<.001	<.001
l.s.d.		0.22	0.03	0.05		0.03	0.07
	12	0.04	0.33	0.15	0.04	0.33	0.29
	30	0.23	0.61	0.39	0.08	0.43	0.66
	36	1.80	0.46	1.08	0.19	0.30	0.82
	F prob	<.001	<.001	<.001	<.001	<.001	<.001
	l.s.d.	0.19	0.03	0.05	0.02	0.03	0.06
	12	0.02	0.30	0.14	0.04	0.27	0.39
0	30	0.29	0.45	0.45	0.12	0.29	0.78
	36	1.69	0.40	1.09	0.20	0.25	0.84
	12	0.05	0.35	0.16	0.05	0.35	0.27
400	30	0.32	0.59	0.44	0.05	0.33	0.76
	36	2.60	0.45	1.10	0.2	0.32	0.87
	12	0.05	0.35	0.15	0.04	0.40	0.21
800	30	0.20	0.66	0.38	0.10	0.49	0.60
	36	1.64	0.45	1.16	0.19	0.25	0.74
	12	0.05	0.31	0.16	0.04	0.30	0.28
1600	30	0.12	0.73	0.29	0.07	0.61	0.50
	36	1.28	0.53	0.98	0.17	0.38	0.84
F prob		<.001	<.001	0.03	0.03	<.001	0.01
l.s.d.		0.38	0.05	0.09	0.04	0.05	0.12

Shoot dry matter and Ca% increased between day 12 and 36, while shoot P% increased until day 30 after which there was a reduction. The elevated shoot P%, near day 30, was even evident in the zero P control (Table 3-7). Phosphorus is required in higher concentrations in young and growing tissue than mature tissue while Ca concentration is usually greater in mature tissue (Klobe and Stephan-Beckmann, 1997). The observed changes during time in the distributions of Ca and P would be expected during normal growth.

Liquid starter solution rates of up to P 400 mmol can significantly improve the early growth of potato shoots during the first 30-40 days after planting, even when substantial quantities of P have been applied in the conventional band (Table 3-7).

This finding supports the case that some degree of P deficiency is occurring even in the presence of high rates of P banded in the conventional position. The optimum rate of liquid starter P (400mmol P) is almost four fold higher than that found when soils treated with starter solutions were maintained above field capacity (Table 3-1 p 57).

3.4 Discussion

When soils moistures are greater then field capacity a large reduction in root growth occurred when the rates of MAP liquid starter solutions were higher than 100 mmol. While it was likely that a low calcium activity ratio (CAR) could have caused the reduction in root growth, salinity could be equally implicated. However, a soil solution salinity of more the 4 dS m^{-1} was required from the phosphorus acid solutions (Table 3-2 p 61) before effects on root growth were found. Root growth reduction was apparent from MAP treated soil when salinities were only 2.2 dS m^{-1}. This finding suggests that low calcium activity rather than salinity was inhibiting the root growth from MAP starter liquids. The range of CAR for the onset of root length reduction, CAR 0.05-0.13, is similar to the value of 0.05 found by Moody *et al.* (1995b) for soybean root growth. The inclusion of a soluble calcium salt such as calcium nitrate should be considered when using ammoniated phosphates in starter bands to increase the calcium activity ratio.

The highest root lengths from the phosphorus acid treatments were obtained from the 35 mmol P starter solution. There was no direct evidence as to whether the root length reduction from higher phosphorus acid rates was due specifically to Mn or Al toxicity; regressions of root length against both Al^{3+} ($R^2 = 0.28$) and Mn^{2+} ($R^2 = 0.45$) were low. Mn concentrations in the shoot tissue were well below the levels for Mn toxicity (Foy *et al.,* 1988). Further studies using more refined root growth methods would be require to show if Al or Mn was the cause of the root length reduction.

The use of phosphorus acid rather than phosphoric acid may have influenced the growth and response of the plants. This is probably not as important for the laboratory trial since the acidifying effects of each acid is similar, the pH trends of the treated soil would be alike regardless of the P source. Phosphoric acid was to be

used for the field trial, but could not be sourced before planting and was substituted for with phosphorous acid. Phosphorous acid is not utilised by plants until it has been oxidised by soil organisms to phosphate, a process that takes up to four moths to generate significant amounts of phosphate (Adams and Conrad, 1953). There were only small quantities of phosphate in the phosphorous acid used (0.1 mg PO_4^{3-} per gram). There are, however, large reserves of phosphate in exchangeable forms adsorbed in ferrosol soils. Sulphate, though less tightly bound than phosphate (Wiklander, 1965; Spotsito, 1989), was desorbed by the application of phosphorous acid (Figure 3-8) and sulphate applications can release sufficient amounts of adsorbed P for yield responses (Menary and Hughes, 1967). The application of phosphorous acid is then likely to release a quantity of previously adsorbed phosphate by anion exchange. Such desorbed phosphate may have contributed to the observed plant response to P. The soil solution P concentration from the optimum phosphorous acid application was 320 mmol P. Maximum growth of potato plants occurs from P concentrations of 16-60 ¼mol P (Houghland, 1947 cit in Asher and Loneragan, 1967). Only 5% of the total P in the soil solution would need to be desorbed ortho-phosphate P for P to be non limiting.

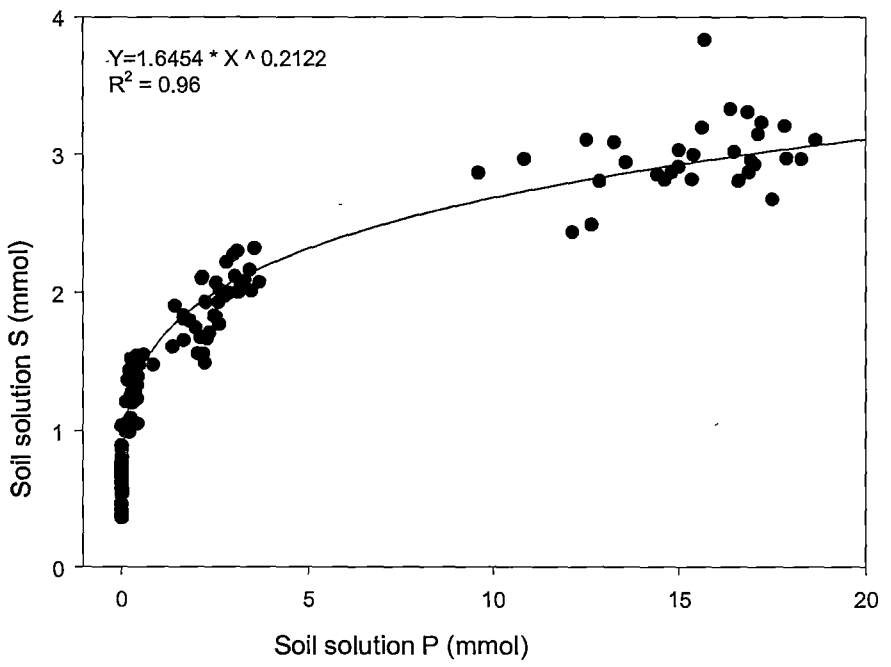


Figure 3-8. Desorption of sulp h ate following additions of phosphorous acid (0 – 320 mmol P) to ferrosol soil.

In the field trial, liquid starter P had no effect on early plant nutrition or tuber yield. The most probable cause was that insufficient P was applied in the starter treatments. Early experiments from plants grown at soil moitures above field capacity yielded optimum starter P concentrations of 35 to 100 mmol (Table 3-1 p 57, Table 3-2 p 61). These findings were used as the basis for the field trial design. However, a glasshouse trial of plants grown at soil moisture levels below field capacity, similar to those likely to occur in the field, indicated the optimum rate of liquid starter P to be up to 400 mmol P and possibly higher (Table 3-7 p 73). The plants were grown for longer periods, over weeks rather than days, which would enable more time for the plants to recover from any initially stressful conditions caused by the higher strength starter solutions. The recurrent wetting/drying phases of the plants grown at lower soil moisture levels, the below field capacity experiments, may have reduced the activity of P and other ions likely to adversely affect root growth when present at high concentrations. The optimum rate of starter liquid P in soil moistures below field capacity is up to five times higher than that used in the field trial and could explain the lack of observed responses in the field trial.

The field trial plot was planted in a paddock of more advanced potatoes. These potatoes were irrigated within days after the liquid starter trial plot had been planted, which was several weeks earlier than would normally occur. Since P uptake is strongly influenced by soil moisture (Baerug and Steenberg, 1971), the wetter conditions are likely to have masked responses that may have occurred to the liquid starter treatments (Reiners *et al.,* 2001). Variation in irrigation rates appeared to have a significant effect on potato growth. Excess irrigation may have caused N leaching, but there was also evidence of variation in soil available P. There was a moderate correlation between Colwell P and organic carbon from all the trial sites (data not shown) which indicates soil available P (Figure AII-0-1 p 154) was improved on plots with higher organic carbon levels. However, the variation in soil P may have been a pre-existing feature that could be caused by topsoil redistribution or previous P fertiliser applications. There were no records of contrasting P fertiliser applications in this unit that may have contributed to the variation in P.

Following the results from Section 3.3 (Figure 3-7 p 71) further work with higher strength liquid starter treatments may be fruitful. Given the strong influence

irrigation has on growth and nutrition (Baerug and Steenberg, 1971; Stark *et al.*, 1993), experiments combining irrigation regimes that moisten the hill soil with dry fertiliser starter treatments could be a valuable approach.

4 Irrigation with dry granular starter phosphorus

The low strength liquid starter fertilisers used in the field trial of 1999 (Table 3-4 p 65) proved unsuccessful. While more concentrated solutions may have succeeded, it was decided to reassess a granular starter P in conjunction with different soil moisture regimes. Adequate soil moisture is essential for root growth and P uptake by reducing the strength of compacted soil (Akram and Kemper, 1979; Gupta *et al.*, 1989) and facilitating phosphorus diffusion and uptake (Jungk and Claassen, 1997; Ozanne, 1980; Vegh *et al.*, 1989). Potato crops are highly responsive to irrigation (Taylor and Ashcroft, 1972; Martin *et al.,* 1992; Stieber and Shock, 1995) and the total P uptake of potatoes can be improved by applying higher rates of irrigation water (Baerug and Steenberg, 1971). Soil moisture is likely to strongly influence the early growth of the potato crop.

Hilling potatoes introduces a drainage pattern on the paddock. The amount of drainage in furrows varies depending on the soil type, with non-wetting and low permeability soils being the most severely affected (Robinson, 1999). Since ferrosols are highly porous and conductive (Isbell, 1994), there is little risk of hilling alone causing excess run off. However, wheel compaction and smearing may reduce the soil's permeability so that run off can occur down the furrows, particularly on steeper slopes (Ressler *et al.,* 1998). Hilling also restricts lateral root growth (Iwama, 1998). Potato root systems are shallow in comparison to other crops (Bishop and Grimes, 1978; Lesczynski and Tanner, 1976; Rab and Willatt, 1987) but can have a wide lateral spread when soil conditions permit (Weaver *et al.,* 1922). Wheel compaction in the furrow soil may further hinder lateral root growth (DeRoo and Waggoner, 1961).

Plant canopies have the potential to redirect rainfall and overhead irrigation (Carter *et al.,* 2000; Ellsbury *et al.,* 1996; Saffigna *et al.,* 1976). The Russet Burbank potato, along with most commercial varieties, has upright stems with large hanging leaflets

and the overall appearance is rather like an umbrella (Potato Marketing Board 1965; Canadian Food Inspection Agency 2002). This shape tends to shift water to the outer edge of the canopy. In comparison corn and carrots, which have funnel shape architecture, tend to concentrate the water around the stem (Carter *et al.,* 2000; Ellsbury *et al.,* 1996). Hence, the shape of the canopies may be affecting the distribution of irrigation water on the soil, which in turn can affect water use efficiency, root growth and nutrient uptake.

4.1 Field trial of hill applied dripper irrigation and overhead sprinkler irrigation with granular starter phosphorus

Fertiliser uptake can be strongly influenced by the soil moisture regime (Saffigna *et al.*, 1977; Stark *et al.*, 1993; Waddell *et al.*, 1999). A field trial was established to compare starter phosphorus treatments in combination with normal overhead irrigation and hill irrigation applied through drippers placed along the hill top. During the trial, information was gathered on the spatial distribution of roots, soil moisture, soil strength and bulk density in potato hills (Section 4.6 p 126), the development of potato plant canopy ground cover, the leaf area covering the ground, (Section 4.2 p 88) and the water shedding property of potato canopies (Section 4.3 p 102).

4.1.1 Methods

An experiment to compare the effects of irrigation by drippers with overhead sprinklers, in combination with starter fertiliser placed as a spot or band, was established at Forthside Vegetable Research Station. A split plot design was used, with irrigation treatments as whole plots and the phosphorus conventional bands or starter placement treatments as sub plots (Figure 4-1). Each starter treatment was replicated four times within an irrigation plot and phosphorus conventional band rates were replicated twice.

The starter P treatments were placed with the sett either as a continuous starter band (B) or as discrete starter spots (S). Control (C) treatments had an equivalent amount of P placed in the conventional banding position (Figure 4-1). Phosphorus at 25 kg P ha^{-1} was applied in each starter treatment (S and B) as single superphosphate (SSP) in the starter position and 75 kg P ha^{-1} as DAP in the conventional band (Figure 2-1).

The control (C) had 25 kg P ha^{-1} as SSP and 75 kg P ha^{-1} as DAP mixed together in the conventional banding position. Nitrogen was supplied as ammonium sulphate at 133 kg N ha^{-1} and DAP at 67 kg N ha^{-1} to give a total nitrogen application of 200 kg N ha^{-1} Table 4-1. Potassium was applied as potassium sulphate at 300 kg K ha^{-1}. Additional conventionally banded P fertiliser rates of 0, 200, and 300 kg P ha^{-1} were included to evaluate the P responsiveness of the site. These treatments were replicated twice within each irrigation plot. Triple super phosphate was used to supply the higher P rates. DAP was omitted from the zero P conventionally banded treatment and an additional N 67 kg ha^{-1} supplied as ammonium nitrate (Table 4-1). The control starter treatment was used as a 100 kg P ha^{-1} rate in the analysis of conventional band rate effects.

Table 4-1. Fertiliser N, P and K rates (kg ha^{-1}) for the sub treatments in the field experiment at Forthside in 2000.

	Starter band	Conventional band						
	P	P			N			K
	SSP	SSP	TSP	DAP	DAP	$(NH_4)_2SO_4$	NH_4NO_3	K_2SO_4
Control		25		75	67	133		300
Band	25			75	67	133		300
Spot	25			75	67	133		300
0						133	67	300
200			125	75	67	133		300
300			225	75	67	133		300

Both starter and conventionally banded fertiliser were applied at planting using a modified Faun® planter. Starter treatments were applied through a separate fertiliser box with a flexible tube that allowed fertiliser placement with the seed or with the conventionally banded fertiliser for the control treatments. A manually operated hinged bucket was used to store and then drop the spot treatment directly over the sett during planting. Each plot was four rows wide by five metres long with a one metre buffer between plots.

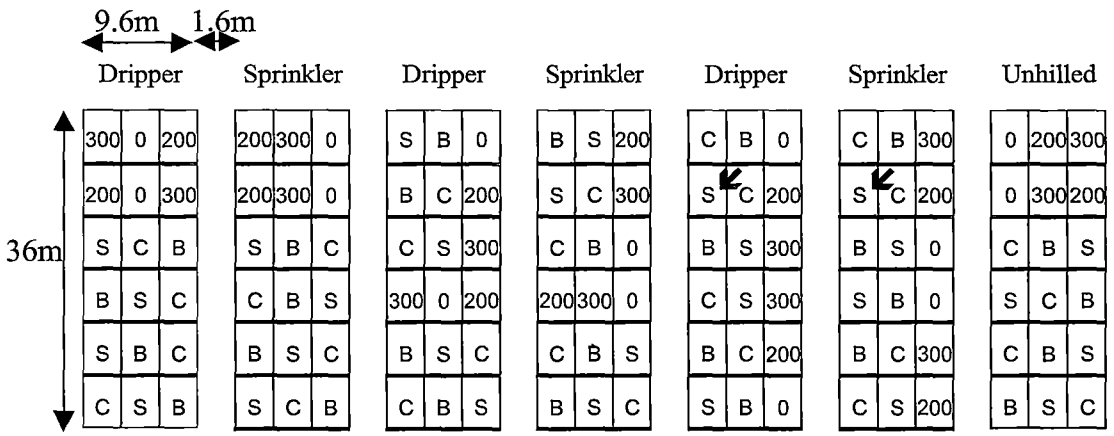


Figure 4-1. Experimental layout for irrigation, starter and conventionally banded rates (C control, B band, S spot). Numbers are P rates in kg ha^{-1} used to establish the P response curve, treatment C = 100 kg P ha^{-1}. The plots on the far right were left unhilled for a comparison of root growth without hilling. ↙ denotes position of tensiometer arrays.

The irrigation plots were twelve rows (9.6 m) wide by 36 m long, comprising three by six sub plots (Figure 4-1). Sprinkler irrigation was applied through two lines of fixed head, gear driven sprinklers placed beside the outside buffer rows, i.e. 9.6 m apart. There were four sprinklers in each line and each sprinkler had a throw of 10-11 m at 200 kPa water pressure. The precipitation rate under the sprinklers was measured to be 35 mm h^{-1}. Sprinklers were run for between 1-1½ hours at each application. Nelson® dripper tape was laid out at one line per row along the top of hills shortly after emergence. The drip line had an emitter spacing of 300 mm and a flow rate of 2.5 l h^{-1} giving the equivalent precipitation rate at 800 mm row spacing of 10.4 mm h^{-1}. The drippers were usually run for one hour, though on occasion they were run for up to two hours.

Soil matric potential was monitored by tensiometers. Three tensiometers were placed at 250 mm, 375 mm and 500 mm below the top of the hill and another two tensiometers at 250 mm and 375 mm below the surface of the furrows. The tensiometer arrays were installed in duplicate in one dripper plot and one sprinkler plot (Figure 4-1). Tensiometers were constructed from a porous ceramic Soilspec® tensiometer tip, an appropriate length of 25 mm diameter electrical conduit, and a 100 mm long by 15 mm diameter clear acrylic tube. Soilspec® tensiometer tube stoppers were used to seal the tensiometers. The tensiometers were read every two to

five days using a vacuum gauge fitted with a hypodermic needle. The vacuum gauge was calibrated against a mercury manometer. Dripper flow rate was monitored by collecting the water from an emitter in the dripper plot and sprinkler irrigation monitored by catch cans placed across the sprinkler plot prior to irrigation. The crops were irrigated when the average soil water tension at 250-375 mm below the top of the hill was -40 kPa (Cotching, 1997).

Soil samples were collected during the early stages of crop senescence from depths of 250, 350, 450, 600 and 800 mm directly below the centre of the hill with a 100mm diameter soil auger. There were six replicates in each of a dripper and sprinkler plot. The samples were air dried, ground and water-soluble nitrate was extracted in 1:5 soil water solution after a one-hour shake. Nitrate was measured by automated colour (Section 3.1.1 p 54) and potassium and sulphur by ICPES (Section 3.1.1 p 54).

The crop was planted on 9/11/00 with approximately 50% emergence on 29/11/00 (Table 2-2 p 43). Full canopy closure commenced around 2/1/01 and senescence began between 27/2/01 and 5/3/01. The crop was harvested during 11-12/4/01. Petiole sampling and tuber analysis are described in Table 2-2 p 43. Digital images of crop ground cover were taken at regular intervals during crop growth (Section 4.2 p 89). Differences in the ground cover were used to measure the effects of fertiliser and irrigation treatments on plant growth. Soil samples were collected several weeks prior to planting on a sampling grid 4.5 m by 3.6 m over a unit of 36 m by 80 m. Soil samples were analysed for Colwell P and K and a subsample analysed for organic carbon (Table 4-10 p 135). An unreplicated subplot comprising potatoes planted at a depth of 200 mm without hilling was included, primarily to investigate root development in the absence of hills (Section 4.6 p 129). The paddock had been previously planted to carrots. Results were analysed by a split plot ANOVA with irrigation being the whole plot and starter band and conventional band treatments being the split plots.

4.1.2 Results

There were no effects of the starter treatments on petiole nutrition other than a small increase in nitrogen in the banded starter treatment (Table 4-2). The ground cover

was significantly larger in the control treatment than the spot treatment during the establishment phase (Table 4-2). During the senescence phase there was a tendency for the spot starter treatment to have a larger ground cover. A similar trend of smaller ground cover during establishment, but larger ground cover at senescence, was also observed with the nil P treatment (Table 4-3). There were no significant interactions between irrigation method and starter fertiliser placement.

Table 4-2. Effect of starter phosphorus treatments and irrigation method on petiole nutrient content, canopy ground cover during establishment (31-52 DAP) and senescence (115 DAP) and tuber P%.

					Petiole			Ground cover		Tuber
Irrigation	Starter P placement	P (%)	N (%)	Ca (%)	K (%)	Mg (%)	Weight (mg)	Dap 31-52	Dap 115	P (%)
Dripper		0.29	3.2	0.96	12.4	0.38	134	0.62	0.46	0.15
Sprinkler		0.25	3.4	0.97	12.3	0.39	132	0.62	0.59	0.16
F prob		NS	NS	NS	NS	NS	NS	NS	0.021	NS
l.s.d.									0.08	
	Band	0.27	3.4	0.98	12.3	0.39	133	0.62	0.51	0.16
	Spot	0.27	3.2	0.95	12.4	0.39	130	0.61	0.56	0.15
	Control	0.27	3.3	0.96	12.3	0.39	136	0.63	0.51	0.16
	F prob	NS	0.013	NS	NS	NS	NS	0.029	NS	NS
	l.s.d.		0.14					0.016		
	Band	0.28	3.3	0.96	12.3	0.38	137	0.62	0.44	0.15
Dripper	Spot	0.30	3.0	0.94	12.5	0.39	131	0.61	0.50	0.15
	Control	0.29	3.1	0.98	12.5	0.38	135	0.63	0.49	0.16
	Band	0.25	3.5	1.00	12.3	0.40	130	0.62	0.59	0.16
Sprinkler	Spot	0.25	3.3	0.96	12.3	0.39	128	0.61	0.62	0.16
	Control	0.26	3.4	0.94	12.2	0.40	137	0.64	0.58	0.16
F prob		NS	NS	NS	NS	NS	NS	NS	NS	NS

Phosphorus deficiency tends to reduce early vigour and delay senescence in potatoes (McCollum, 1978; Jenkins and Ali, 1999) and soybean (Gutierrez-Boem and Thomas, 1999). This is an indication that the spot treatment may have reduced the availability of starter applied P. However, there was no difference in the petiole P concentrations between starter treatments. Tuber P was also not affected by the starter treatments (Table 4-2).

There were increases in petiole P%, K% and petiole weight and in tuber P% from higher rates of conventionally banded P (Table 4-3). Ground cover development was lower at establishment but higher at senescence in the zero P treatment compared to

the higher rates of P. The effects of irrigation source were larger in the conventional banding rate comparison than with the starter treatments. Drip irrigation tended to increase petiole P and petiole weight. There was also an increase in the establishment phase ground cover from drip irrigation (Table 4-3) and a corresponding decrease in ground cover at senescence. There were no significant interactions between irrigation method and conventional banded P rate.

Table 4-3. Effect of convention a lly banded treatments and irrigation method on petiole nutrient content, canopy ground cover during establishment (31-52 DAP) and senescence (115 DAP) and tuber P%.

		Petiole						Ground cover		Tuber
Irrigation	Conventional P Rate (kg ha^{-1})	P (%)	N (%)	Ca (%)	K (%)	Mg (%)	weight (mg)	Dap 31-52	Dap 115	P (%)
Dripper		0.29	0.33	0.97	12.3	0.38	135	0.59	0.48	0.16
Sprinkler		0.24	0.33	1.00	11.8	0.39	123	0.57	0.64	0.16
F prob		0.054	NS	NS	NS	NS	0.049	0.029	0.042	NS
l.s.d.		0.05					11.4	0.016	0.14	
	0	0.17	0.35	0.91	10.8	0.43	64	0.35	0.78	0.15
	100	0.27	0.33	0.96	12.3	0.39	136	0.63	0.51	0.16
	200	0.29	0.33	0.99	12.2	0.35	149	0.64	0.45	0.16
	300	0.32	0.32	1.08	12.5	0.31	160	0.66	0.54	0.18
	F prob	<.001	NS	NS	<.001	0.002	<.001	<.001	<.001	0.005
	l.s.d.	0.012			0.22	0.03	16	0.027	0.117	0.014
	0	0.17	0.38	0.89	11.4	0.42	74	0.40	0.66	0.15
Dripper	100	0.29	0.31	0.98	12.5	0.38	135	0.63	0.45	0.15
	200	0.31	0.35	0.97	12.3	0.34	157	0.65	0.41	0.16
	300	0.39	0.31	1.03	12.7	0.36	173	0.66	0.44	0.18
	0	0.17	0.33	0.93	10.3	0.44	55	0.31	0.90	0.15
Sprinkler	100	0.26	0.34	0.94	12.2	0.40	137	0.64	0.58	0.16
	200	0.26	0.32	1.01	12.0	0.35	142	0.63	0.49	0.17
	300	0.25	0.33	1.13	12.3	0.34	147	0.65	0.65	0.18
F prob		<.001	0.087	NS	0.017	NS	NS	NS	NS	NS
l.s.d.		0.018			0.56					
l.s.d.*		0.017			0.31					

* l.s.d. value is for comparison of treatments with the same level of irrigation.

There was a significant increase in the petiole P% with increasing phosphorus rates between 0 kg P ha^{-1} and 100 kg P ha^{-1} in both the dripper and sprinkler irrigated treatments. Petiole P continued to increase from higher rates of P under the dripper irrigation but not with sprinkler irrigation (Figure 4-2). Dripper irrigation has improved the availability of the conventionally banded P without affecting P availability from the starter bands. Since petioles were collected at the 10-20 mm

tuber stage only, it is not known if the higher P nutrition occurring under drip irrigation continued throughout the life of the crop. However, tuber P% shows no interaction with irrigation source, hence the irrigation source effect on phosphorus uptake did not persist into tuber bulking.

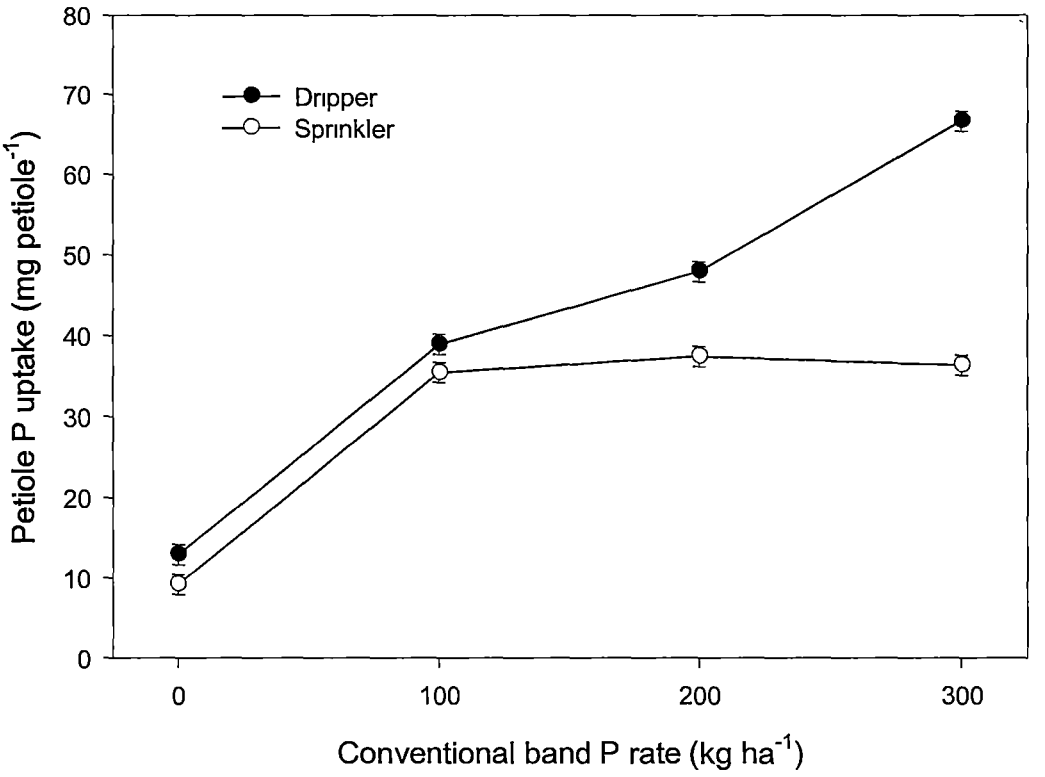


Figure 4-2. Petiole P uptake from conventionally banded phosphorus under sprinkler and dripper irrigation. Bars are l.s.d. at P = 0.05.

There were few effects of starter P on tuber yield and size grades. The dripper control treatment yielded significantly more tubers in the 150-250 g size range; however, there was no effect of starter P on total or ware tuber yields (Table 4-4). There were no conventional banding P rate by irrigation interactions on tuber yield or size grades (Table 4-5). The largest effect of conventionally banded P rate occurs between the 0 kg P ha^{-1} and higher P rates. The total and ware yields were significantly higher in the 300 kg P ha^{-1} treatment than either the 100 and 200 kg P ha^{-1} treatments. Most of the yield increase attributed to higher rates of conventional band P came in the 75-150 g and 150-250 g tuber size grades. However, there was a trend for more 250-450 g tubers at the highest rate of P 300 kg ha^{-1}. Tuber specific gravity was high and unaffected by starter treatments, conventionally banded phosphorus rates or irrigation.

Table 4-4. Effect of starter phosphorus treatments and irrigation method on tuber size grades, total and ware yields (t ha^{-1}) and specific gravity.

Irrigation	Starter P placement	<75 (g)	75-150 (g)	150-250 (g)	250-450 (g)	>450 (g)	Reject yield	Total yield	Ware yield	Specific gravity
Dripper		1.40	7.53	22.9	22.2	2.29	1.84	58.0	54.8	1.088
Sprinkler		1.57	8.03	22.5	23.1	2.88	3.30	61.4	56.5	1.089
F prob		NS	NS	NS	NS	NS	NS	0.07	NS	NS
l.s.d.								4.1		
	Band	1.53	7.46	22.4	22.7	2.26	2.80	59.1	54.8	1.088
	Spot	1.50	7.96	21.8	23.5	2.75	2.33	59.7	55.9	1.088
	Control	1.42	7.90	24.0	21.8	2.73	2.60	60.3	56.3	1.089
	F prob	NS	NS	0.02	NS	NS	NS	NS	NS	NS
	l.s.d.			1.4						
	Band	1.46	7.43	23.6	21.3	1.43	2.08	57.3	53.8	1.089
Dripper	Spot	1.34	7.6	20.8	23.2	3.06	1.74	57.6	54.5	1.088
	Control	1.39	7.54	24.3	22.0	2.38	1.71	59.3	56.2	1.089
	Band	1.60	7.50	21.2	24.0	3.10	3.54	61.0	55.8	1.088
Sprinkler	Spot	1.66	8.31	22.7	23.8	2.43	2.91	61.9	57.3	1.089
	Control	1.45	8.26	23.6	21.6	3.09	3.48	61.4	56.5	1.089
F prob		NS	NS	0.02	NS	NS	NS	NS	NS	NS
l.s.d.				7.6						
l.s.d.*				1.9						

* l.s.d. value is for comparison of treatments with the same level of irrigation.

Irrigation source had no effect on total or ware yields, though there was a near significant (P=0.052) effect of irrigation source on the quantity of reject tubers. Drip irrigation reduced the quantity of reject tubers. Intermittent periods of water deficit increase the occurrence of secondary growth (Moorby *et al.,* 1975). The more frequent water applications through the dripper irrigation system may have reduced the periods of water stress and so reduced the incidence of secondary growth.

While there were no effects of starter P on nutrition or yield, the proportion of ground cover during the establishment phase was affected by the starter treatments. There was a significant reduction in average ground cover of the spot starter treatment (Table 4-7 p 97). The yields of both petioles and tubers were reduced by the starter treatments, though not significantly. Starter placed P appears to be no more effective, and possibly less effective than conventional band placed P.

Table 4-5. Effect of conventionally banded phosphorus rates and irrigation method on tuber size grades, total and ware yields (t ha^{-1}) and specific gravity.

Irrigation	Conventional P Rate (kg ha^{-1})	<75 (g)	75-150 (g)	150-250 (g)	250-450 (g)	>450 (g)	Reject yield	Total yield	Ware yield	Specific gravity
Dripper		1.42	7.69	23.9	22.3	2.55	1.91	59.8	56.4	1.088
Sprinkler		1.46	7.94	22.7	21.9	3.59	3.06	60.2	55.6	1.089
Fprob		NS	NS	NS	NS	NS	0.052	NS	NS	NS
l.s.d.							1.17			
	0	1.27	5.74	17.8	20.1	4.34	3.25	52.5	48.0	1.088
	100	1.42	7.90	24.0	21.8	2.73	2.59	60.3	56.3	1.089
	200	1.63	8.73	24.4	21.2	2.96	2.03	61.0	57.3	1.089
	300	1.47	8.79	25.3	25.5	2.60	1.99	65.6	62.2	1.089
	F prob	NS	0.054	0.006	0.08	NS	NS	0.002	<.001	NS
	l.s.d.		2.07	3.5	3.7			4.7	4.1	
	0	1.15	5.59	17.8	20.3	3.63	2.66	51.1	47.3	1.088
Dripper	100	1.39	7.54	24.3	22.0	2.38	1.71	59.3	56.2	1.089
	200	1.58	9.09	26.6	21.0	2.29	1.50	62.1	59.0	1.089
	300	1.58	8.69	26.5	26.2	2.09	1.96	67.0	63.5	1.089
	0	1.40	5.90	17.9	20.0	5.04	3.84	54.0	48.8	1.088
Sprinkler	100	1.45	8.26	23.6	21.6	3.09	3.46	61.4	56.5	1.089
	200	1.67	8.38	22.3	21.4	3.63	2.54	59.9	55.7	1.089
	300	1.35	8.90	24.1	24.8	3.10	2.03	64.2	60.8	1.090
F prob		NS	NS	NS	NS	NS	NS	NS	NS	NS

Irrigation scheduling, soil matric potential, rainfall, and evaporation are shown in Figure 4-3. Soil matric potential was maintained at or below -45 kPa, the upper target to commence irrigation was -40 kPa. Rainfall between November 2000 and February 2001 was only 53% of average and evaporation over the same period was 9% higher than average. A total of 310 mm of water was applied by the drippers and 580 mm by the sprinklers to produce the same yield of tubers. Similar efficiencies have been found in comparisons of drip to sprinkler irrigation for potatoes (Martin *et al.,* 1992; Waddell *et al.,* 1999) and for other crops (Moynihan and Haman, 1992). The average total application for the other potato crops in adjoining units and paddocks at Forthside during the 2000-2001 season was 450 mm. The sprinkler irrigation rate of this trial was 30% higher than that used in adjacent potato crops. However, it was likely that more water than was necessary was applied through the drippers, since there was evidence of nitrate leaching under the drippers (Figure 4-4). Virtually all the nitrate has been removed from the rooting depth (approximately 500 mm depth) and deposited at 600 mm and deeper below the dripper irrigated crop. Hence, some fertiliser N may have become unavailable to the drip irrigated plants.

Potassium, which is less mobile than nitrate (Brady, 1990), has moved downward but has not been displaced below the root zone. Sulphur also shows some degree of downward leaching.

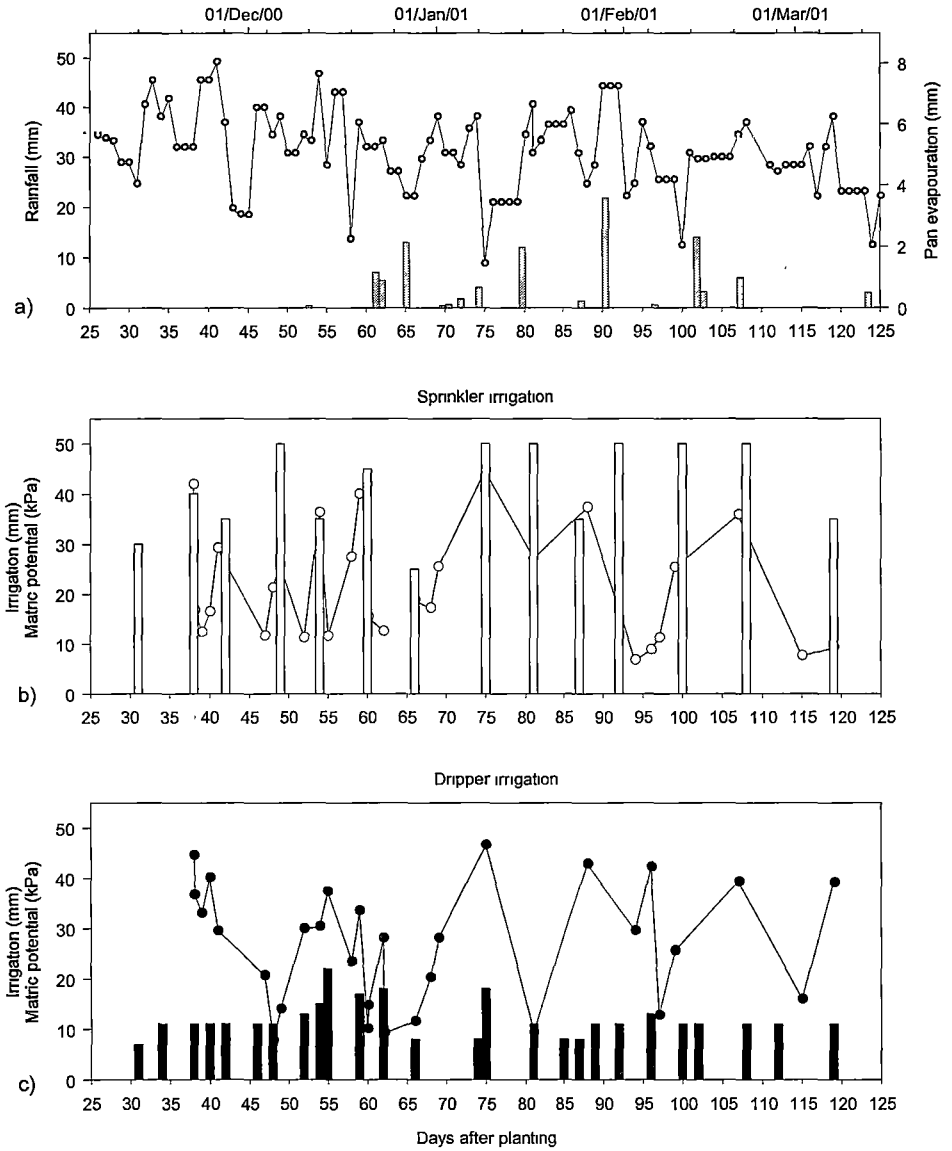


Figure 4-3. a) Rainfall (bars) and daily pan evaporation (line), b) sprinkler irrigation rate (bars) and mean tensiometer tension (line) at 250-375 mm, c) dripper irrigation rate (bars) and mean tensiometer tension (line) at 250-375 mm.

The differential movement of nitrate with irrigation source confounds the interpretation of the earlier senescence of the drip-irrigated crop. Early senescence may be caused by higher availability of P (Jenkins and Ali, 1999), by a reduced

availability of N (Marschner, 1986) or an earlier onset of irrigation (Cappaert *et al.*, 1994). Lower nitrogen levels under the drippers may have contributed to the earlier senescence of the drip irrigated crop. Smaller and more frequent irrigation with the drippers, and the supply of part of the N through fertigation may reduce the risk of N leaching from dripper irrigated crops (Shock *et al.*, 1999).

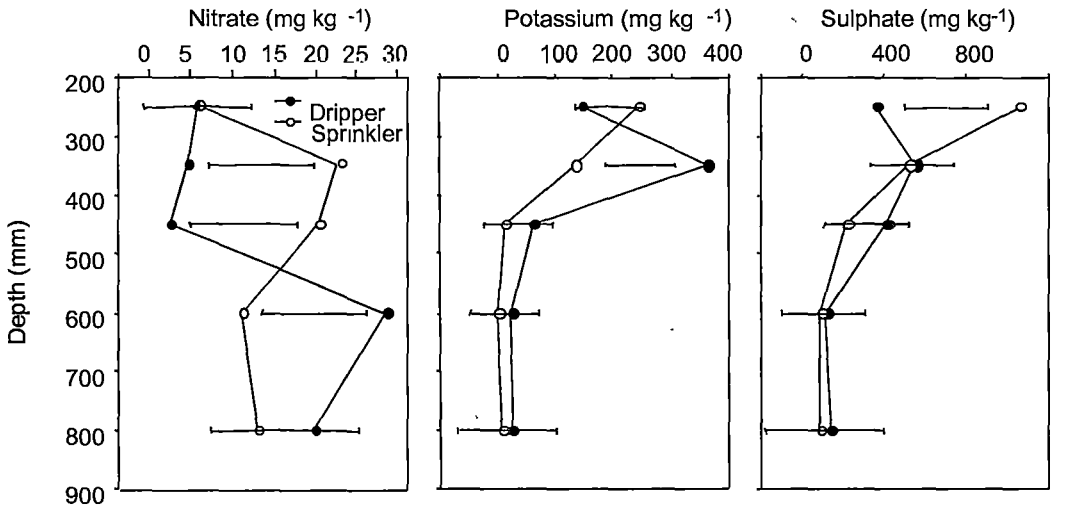


Figure 4-4. 1:5 water extractable ions sampled down the hill centre after crop senescence. Left nitrate, centre potassium, right sulphate. Error bars are l.s.d. at P = 0.05.

4.2 Potato canopy ground cover

Field experiments from Forthside 1999 had indicated that phosphorus and possibly, nitrogen nutrition significantly affected potato canopy development (Figure 3-6 p 68). Phosphorus deficiency tends to reduce early vigour and delay senescence in potatoes (McCollum, 1978; Sparrow and Salardini, 1997; Jenkins and Ali, 1999; Allison *et al.*, 2001). Traditional methods to assess canopy growth rates, such as Leaf Area Index (LAI) and plant biomass require regular destructive sampling (Ngouajio *et al.*, 1999) and are therefore difficult to justify on small trial plots. Recently, methods using digital imagery (Ewing and Horton, 1999; Lukina *et al.*, 1999; Adamsen *et al.*, 1999) greatly reduced the time required to acquire information on plant canopy growth. Since no samples need to be removed, repeated measurements can be carried out on the same stand of plants. Plant ground cover can be used for an assessment of treatment effects, or combined with temperature and

solar radiation data in order to asses the effects of ground cover on crop yield (Sale, 1973; Allen and Scott, 1980; Jenkins and Ali, 1999).

4.2.1 Methods

Digital images were collected at two to three week intervals from the irrigation starter P field trial (Section 4.1.1 p 78). Photographs were taken with a digital camera (Sony Mavica MVC-FD91e) from 2.5 m above the crop while standing on a ladder. Each photo covered an arca of 2.32 m x 1.74 m, in an image of 640 x 480 pixels. Images were collected a total of nine times across the whole trial representing growth stages from 50% emergence to late, but not complete senescence. An additional three sets of images were acquired for the zero P control plots between 2/2/01 and 27/3/01, since the zero P plots were later to achieve full canopy closure. No measurements were made after day 124 due to weed regrowth; however, there were still some green stems present at tuber harvest on 6/4/01, day 146.

All images were kept at the same scale by maintaining a constant photographing height and camera focal length. Each plot was referenced by a peg aligned at the lower right hand corner of the image. It was necessary to crop 40 pixels off the top and bottom of the images, to 640 x 400 pixels, to remove plants from neighbour plots. Trial design, crop establishment and management are previously described (Section 4.1 p 78). Weeds were removed from the photographed plot areas by hand pulling and cultivation where possible. Ground cover results were analysed by an ANOVA split plot design (Genstat 4.2) with irrigation treatment as the whole plots and fertiliser conventional band rate or starter band position as the sub plots.

The main objective when analysing digital images of plant canopies is to separate the areas covered by green leaves from all other components in the image, mostly soil but which may also include dead plant materials. Some of the technical aspects of the analysis of crop images are described by (Ewing and Horton, 1999). The process chosen for the present study involved separating the image into its red, green and blue colour components, where each component is displayed as a separate 8 bit grey scale image. An area in the image containing a leaf has a high green value but a corresponding low red value. Conversely, areas of soil have high red values but low green values (Figure 4-5).

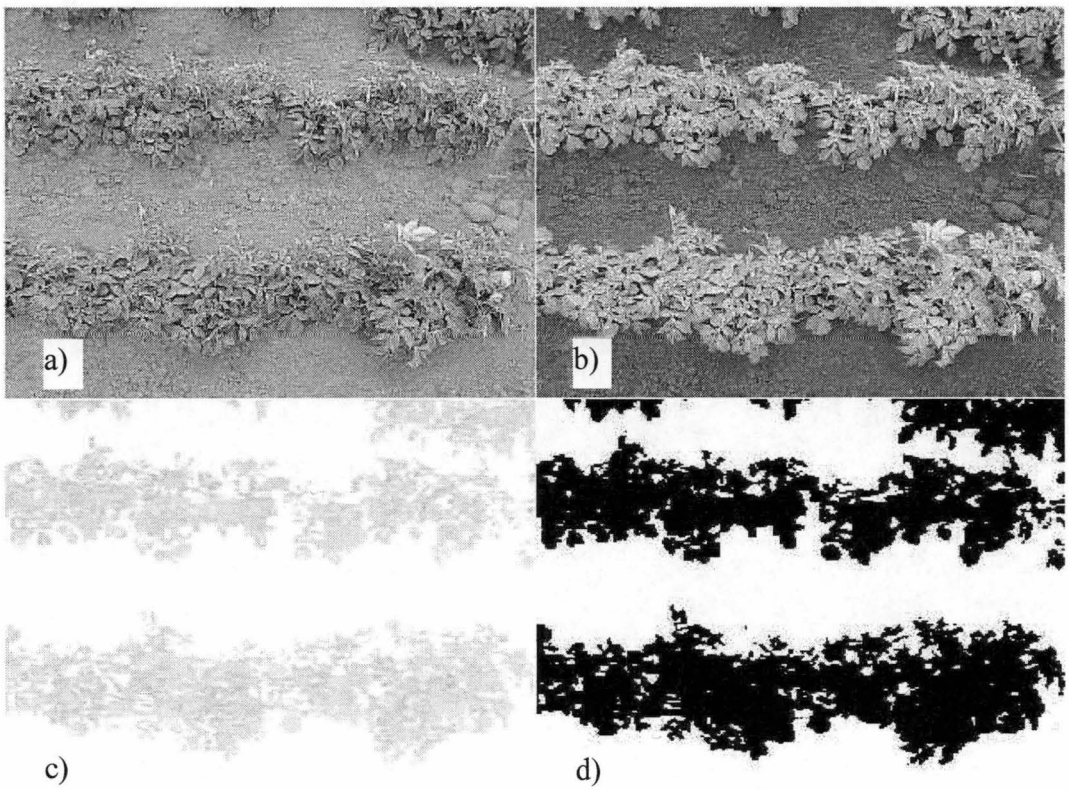


Figure 4-5. Conversion process for calculating ground cover, a) red component, b) green component, c) raw difference (green-red) image with negative values set to zero, d) difference image after thresholding. The ground cover of this image is 0.414.

To utilise this difference a mathematical subtraction was conducted between the green and red components. The result, the difference between the green and red values, is used to calculate the ground cover. If the red value exceeds the green value, indicating a region of soil, the result is set to zero. The difference between green and red remains relatively constant across a wide range of light intensity, i.e. exposure in the picture. However, the difference becomes progressively less reliable at very high or very low light intensity (Figure 4-7). Extremes in light exposure should be avoided. As a rule if you cannot visually discriminate a difference in the image then neither will the image analysis program (Ewing pers comm).

By using a subtraction process there is no requirement for a thresholding step, since the image has already been segregated into regions where green > red (canopy) and where red > green (soil) (Figure 4-5). Hence, any pixel with a difference value more than zero is designated part of the canopy. This process may not be applicable for all

soil and crop combinations and a range of methods should be tried (Ewing and Horton, 1999). A binary threshold step is required to convert the image from greyscale to binary. All image manipulation was carried out with Scion Image® software. Macro programs (Visual Basic) were used to automate image conversion from JPEG to bit map format and to carry image manipulation in Scion Image®. The output is given as the fraction of area covered by green leaves and is hereafter called the ground cover.

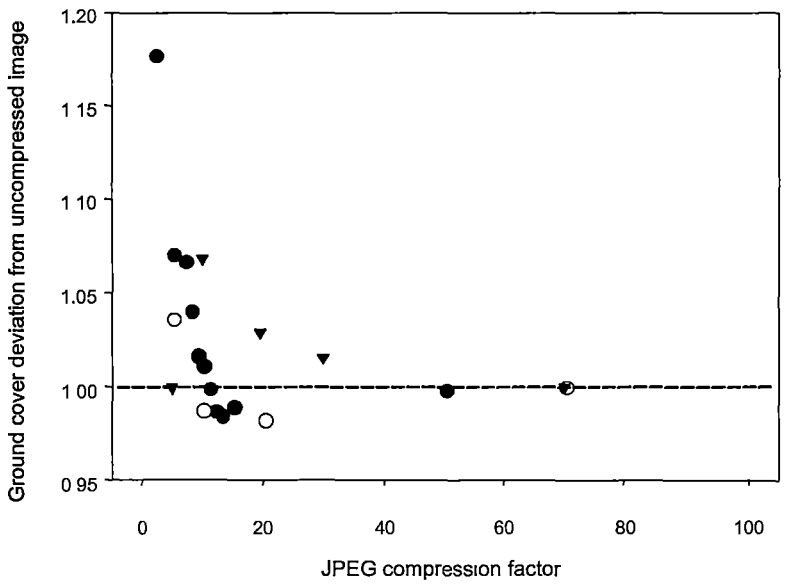


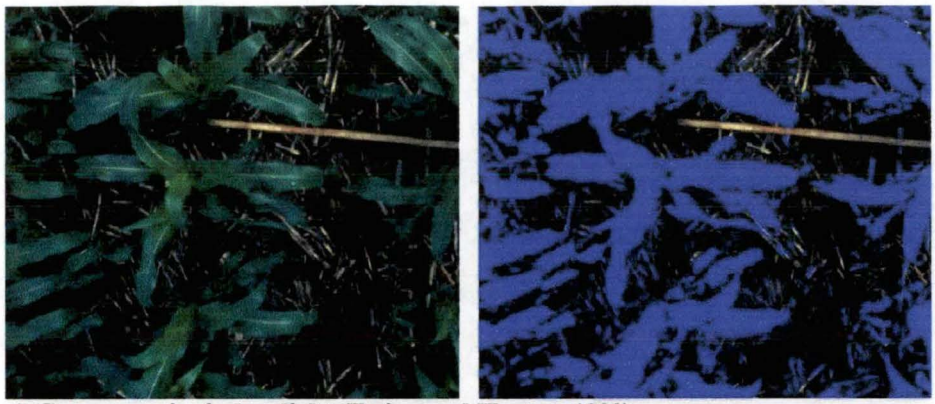
Figure 4-6. Effect of JPEG compression factor on the canopy area measurement of three images with ground cover 0.05(▼), 0.40 (○) and 0.82 (●).

An analysis was made on the effects of prior JPEG compression on the resultant ground cover, which was conducted in bitmap format (Figure 4-6). There are unlikely to be detrimental effects of JPEG conversion on the discrimination between canopy and soil unless very severe compression (ratios of 20% or less) are used. The error at 20% compression is less than 5%. Compression values > 70% were used for all JPEG storage.

Further validation of the green-red difference method of image analysis was conducted on a selection of images (Figure 4-7). Four images were chosen to reflect a range of image conditions. In the weeds image (c) the dead leaf material was not selected, while in image (b) there are areas of leaf missed where they reflected strong sunlight. In image (a) there were difficulties discriminating crop from soil in the

heavily shaded areas. Green plants were successfully selected in image (d) although the soil has a green hue.

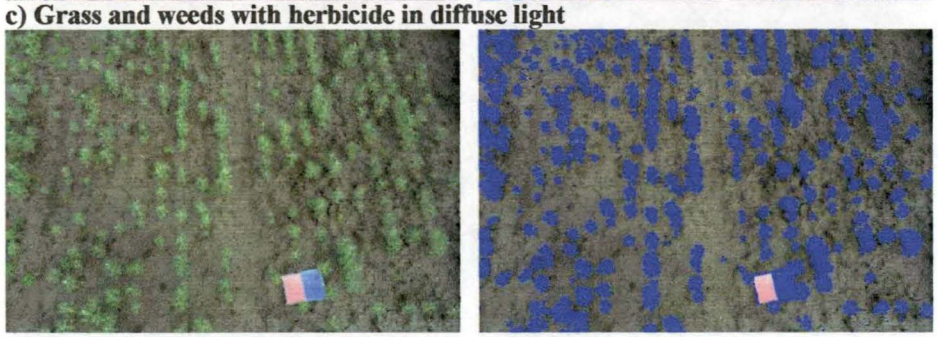
Ewing and Horton, (1999) used multi dimensional principal components analysis to define areas of interest, plant canopy, from other regions, soil etc. While their approach is more rigorous and universal in its application, it is not yet available in a form where large numbers of files can be automatically processed as was required for this study.



a) Corn canopies in low light (Ewing and Horton, 1999)

b) Potato canopies in strong light

c) Grass and weeds with herbicide in diffuse light



d) Lupin seedlings in diffuse light

Figure 4-7. Digital image separation of a selection of images showing original picture (left) and green area selected by green-red method (right).

4.2.1.1 Yield prediction

Tuber yield can be estimated from the sum of solar radiation intercepted by the crop (Allen and Scott, 1980). Intercepted solar radiation is calculated by multiplying the proportion of radiation intercepted by the crop by the available solar radiation during each time period (Allen and Scott, 1980). The proportion of radiation intercepted by the crop is a relationship of leaf area index (LAI), canopy structure and row spacing (Edwards and Ascher, 1982). Since photosynthetic activity is concentrated in the outer leaves of the canopy (Edwards and Ascher, 1982), the leaves measured in the ground cover, being a composite of outside and mid layer leaves of the canopy, are the largest contributors to net photosynthesis. The inner shaded leaves contribute proportionally less, approximately 0.25 of outer leaves (Edwards and Ascher, 1982). Ground cover is essentially the area of leaf exposed to sunlight. It was hypothesised that ground cover, measured by digital camera, should closely approximate the proportion of radiation intercepted by the canopy described by Allen and Scott (1980).

To test the hypothesis that ground cover was equivalent to the proportion of radiation intercepted by the crop combinations of field and modelled data were used. Ground cover and LAI were determined on several field-grown plants at the 15-16 leaf stage. Ground cover was measured from overhead photographs of single plants and leaf area calculated as the sum of individual leaves of those plants. The ground cover of the individual plants and total leaf area were calculated by image analysis by the same process as used for the ground cover analysis. Additional data from a potato plant canopy model (Section 4.3, Figure 4-13 p 107) were used to further establish the relationship and to evaluate the effect of changes in the width of leaflets, since P deficient plants often develop narrower leaflets.

Several methods of crop growth analysis were applied to the ground cover data. Ground cover duration (the integral of the ground cover curve) was calculated by linear interpolation between points on the ground cover curves (method 1). An alternative empirical measure of ground cover duration was made by first fitting regressions of total tuber yield to ground cover values during crop establishment and senescence (method 2). The ground cover values with the highest correlation to final tuber yield were then selected as the respective limits to ground cover duration at

establishment and senescence. These were a ground cover of 0.83 at establishment (R^2=0.23) and a ground cover of 0.10 at senescence (R^2=0.10). Ground cover duration, by method 2, was then calculated as the time interval between the limit at establishment (establishing ground cover > 0.83) and the limit at senescence (senescing ground cover > 0.10). The effects of accumulated day degrees > 9 °C and total intercepted radiation were then investigated on each measure of ground cover duration. Daily soil temperature and solar radiation data were obtained from the Forthside weather station for the period of crop growth.

4.2.2 Results

The location of starter bands had little effect on the ground cover (Table 4-6). There was a small reduction in the ground cover of the spot starter band position compared to the control for the combined analysis of the establishment period (Est). Earlier preliminary pot trials had shown reductions in emergence when fertilisers were placed close to the seed, but these differences tended to diminish with time.

Table 4-6. Effect of starter band position and irrigation method on potato canopy ground cover at establishment and senescence.

Irrigation	Starter band position	Ground cover (days after planting)										
		Establishment							Senescence			
		19	24	31	38	42	52	Est*	107	115	124	Sen*
Dripper		0.011	0.07	0.23	0.47	0.82	0.94	0.42	0.87	0.46	0.11	0.74
Sprinkler		0.014	0.07	0.21	0.52	0.82	0.94	0.43	0.87	0.59	0.27	0.78
F prob		0.03	NS	0.001	<.001	NS	NS	0.05	NS	<.001	<.001	<.001
l.s.d.		0.002		0.01	0.03			0.01		0.06	0.06	0.02
	Control	0.01	0.07	0.22	0.51	0.83	0.95	0.43	0.85	0.51	0.19	0.75
	Band	0.01	0.07	0.22	0.50	0.82	0.94	0.42	0.87	0.51	0.17	0.76
	Spot	0.01	0.07	0.21	0.48	0.81	0.93	0.41	0.88	0.56	0.21	0.77
	F prob	NS	NS	NS	NS	NS	NS	0.02	NS	NS	NS	NS
	l.s.d.							0.014				
Dripper	Control	0.01	0.08	0.23	0.49	0.82	0.94	0.43	0.83	0.45	0.11	0.73
	Band	0.01	0.07	0.23	0.47	0.81	0.93	0.42	0.88	0.44	0.08	0.73
	Spot	0.01	0.07	0.22	0.46	0.81	0.93	0.40	0.9	0.50	0.13	0.75
Sprinkler	Control	0.01	0.07	0.21	0.53	0.84	0.95	0.44	0.87	0.58	0.26	0.78
	Band	0.02	0.08	0.21	0.52	0.82	0.94	0.43	0.86	0.59	0.26	0.78
	Spot	0.01	0.07	0.20	0.51	0.81	0.93	0.42	0.87	0.62	0.29	0.79
F prob		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
l.s.d.												

* average during establishment (Est) and senescence (Sen).

There are variations in the ground cover due to irrigation; however these differences are due more to differences in soil moisture at the time the ground cover was measured than to treatment effects. On day 38 the canopy photos were acquired after the application of the sprinkler irrigation but before drip irrigation was applied. This resulted in a larger difference in the soil matric potential of the two irrigation treatments (Figure 4-3). No matric potential measurements were made before day 38. The drip-irrigated plants were slightly wilted on day 38, which has contributed to a reduction in the ground cover area.

Conventional band P nutrition increased ground cover from day 19 onwards (Table 4-7). Plants with 100 kg P ha^{-1} or more attained a significantly larger ground cover than the control zero P treatments until canopy closure, after day 58. There was an initial trend, until day 31, for the 100 kg P ha^{-1} plants to have a larger ground cover than the higher conventional band P treatments, 200 and 300 kg P ha^{-1}. This pattern was reversed between days 38 and 52 when the 100 kg P ha^{-1} plants had a significantly smaller ground cover than those with higher rates of conventionally banded P. During the senescence phase, from day 107 onwards, the ground cover of the control zero P plants was significantly larger than those with 100 kg P ha^{-1} or more.

Control (zero P) plants under dripper irrigation had a larger ground cover than sprinkler irrigated plants between days 31 and 52 (Table 4-7). Ground cover for all treatments decreased during the senescence period from day 107 onward. There was more variation between measurements at senescence than during establishment, which probably reflects the longer time for plant, climate and soil factors to influence the crop growth and the less ordered growth of the plants (Saffigna *et al.*, 1976). On day 124, higher P rates in conjunction with dripper irrigation gave the smallest ground cover, while zero P under sprinkler irrigation gave the largest ground cover.

Table 4-7. Effect of convention a lly banded phosphorus rates and irrigation method on potato canopy ground cover at establishment and senescence.

Irrigation	Phosphorus Rate (kg ha^{-1})	Ground cover (days after palnting) Establishment 19	24	31	38	42	52	Est*	Senescence 107	115	124	Sen*
Dripper		0.011	0.070	0.23	0.45	0.78	0.90	0.41	0.85	0.48	0.12	0.66
Sprinkler		0.009	0.066	0.20	0.48	0.77	0.88	0.4	0.88	0.64	0.34	0.76
F prob		NS	NS	0.04	NS	NS	NS	NS	NS	0.04	NS	NS
l.s.d.				0.02						0.14		
	0	0.008	0.051	0.13	0.24	0.46	0.61	0.25	0.95	0.78	0.48	0.86
	100	0.013	0.075	0.22	0.51	0.83	0.95	0.43	0.85	0.51	0.19	0.68
	200	0.010	0.070	0.25	0.53	0.86	0.97	0.45	0.82	0.45	0.11	0.63
	300	0.009	0.069	0.25	0.55	0.88	0.98	0.45	0.86	0.54	0.19	0.7
	F prob	0.006	<.001	<.001	<.001	<.001	<.001	<.001	0.01	<.001	<.001	<.001
	l.s.d.	0.003	0.008	0.02	0.04	0.03	0.02	0.01	0.07	0.10	0.09	0.043
	0	0.01	0.05	0.15	0.27	0.51	0.66	0.28	0.93	0.66	0.29	0.77
Dripper	100	0.01	0.08	0.23	0.49	0.82	0.94	0.43	0.83	0.45	0.11	0.64
	200	0.01	0.07	0.26	0.51	0.86	0.97	0.45	0.81	0.41	0.05	0.60
	300	0.01	0.07	0.27	0.52	0.87	0.98	0.45	0.85	0.44	0.06	0.63
	0	0.01	0.05	0.11	0.21	0.41	0.55	0.22	0.98	0.90	0.68	0.94
Sprinkler	100	0.01	0.07	0.21	0.53	0.84	0.95	0.44	0.87	0.58	0.26	0.73
	200	0.01	0.07	0.23	0.56	0.86	0.96	0.45	0.83	0.49	0.18	0.63
	300	0.01	0.07	0.24	0.57	0.89	0.97	0.45	0.87	0.65	0.32	0.77
F prob		NS	NS	NS	0.04	0.01	<.001	<.001	NS	NS	0.05	NS
l.s.d.					0.05	0.04	0.03	0.014			0.25	

* average during establishment (Est) and senescence (Sen).

4.2.2.1 Yield prediction

Potato canopy ground cover closely relates to the proportion of intercepted radiation as used by Allen and Scott (1980) for potato crops. The proportion of ground cover at different leaf are index (LAI) from potato plants grown at the Forthside 2000 trial, and estimates obtained from the modelled data, fitted directly onto the relationship described by Allen and Scott (1980) of the proportion of intercepted radiation as a function of LAI (Figure 4-8). Field measurements had slightly smaller ground cover than those predicted by the model but were comparable to those of Allen and Scott (1980).

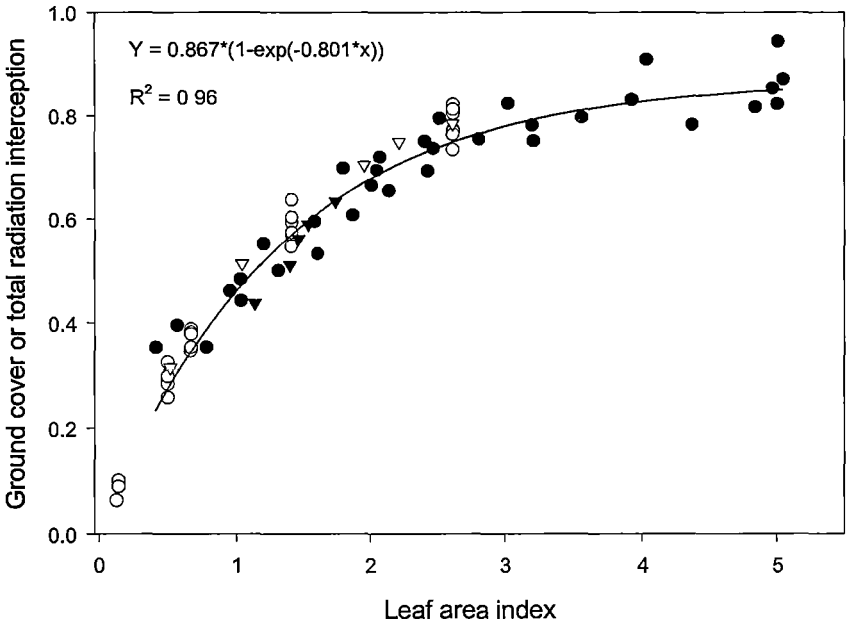


Figure 4-8. Comparison of the proportion of intercepted radiation against LAI, (●) Allen and Scott (1980) and ground cover against LAI (▼) Forthside 2000 (field measurements at the 5, 6, 10, 11, 15 and 20 leaf stage), (○) model estimated ground cover against LAI 15 leaf stage and (▽) 20 leaf stage with leaves 0.2 x normal width.

Reducing the leaflet width to one-fifth the original setting, to gauge the effect of narrower leaves on P deficient plants, produced no obvious deviation from the ground cover to LAI curve (Figure 4-8). Phosphorus deficiency does not influence the relationship between LAI and the proportion of radiation intercepted by the crop.

Leaf area duration gave a poor correlation with total tuber yield (Table 4-8, Figure 4-9). The correlation for day degrees was better at 0.55 and 0.51 from canopy duration methods 1 and 2 respectively. The significance of intercepted solar radiation was increased to R^2=0.54 by allowing phosphorus treatments to have different efficiencies of converting intercepted radiation to assimilates. The resulting conversion rates were 0.76 g MJ^{-1} for plants with phosphorus of 100 kg or more and 0.68 g MJ^{-1} for control no P plants.

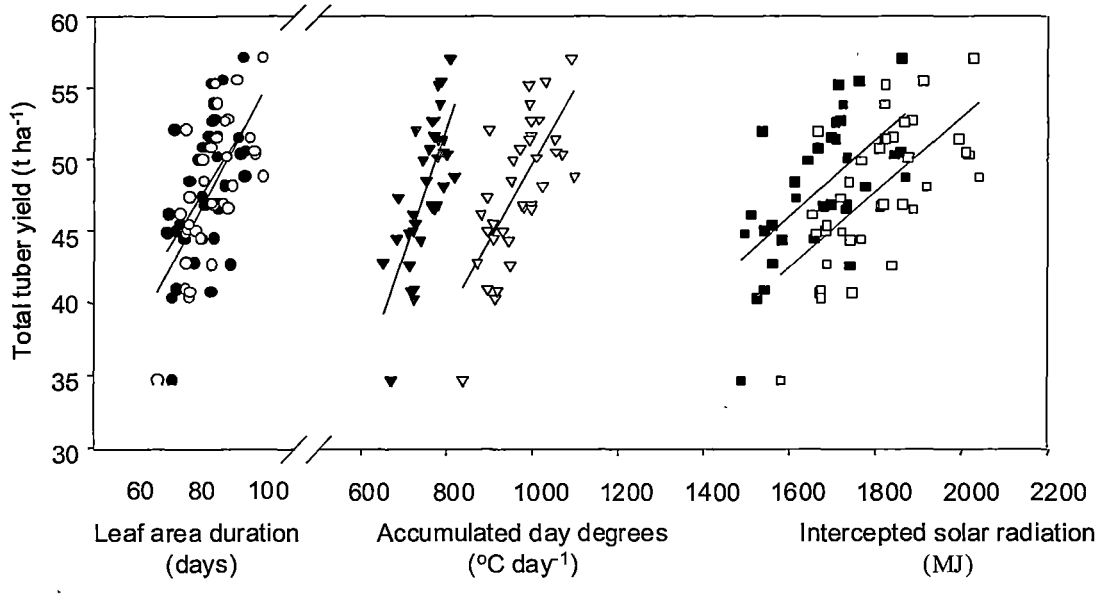


Figure 4-9. Relationship of tuber yield to leaf area duration (●), accumulated day degrees above 9 °C (▼) and intercepted solar radiation (■). Method 1 open symbols, method 2 closed symbols.

The total amount of solar radiation received from 1/9/00 to 30/4/01 was 4040 MJ m^{-2} with daily values ranging from 3-30 MJ m^{-2}. Growing season length, day degrees and accumulated intercepted radiation do not appear to be reliable estimators of yield (Table 4-8).

Table 4-8. Correlation coeffic ients between leaf area duration (LAD), day degrees and intercepted solar radiation, with tuber yields.

		Correlation	
Leaf area	LAD	Day degrees	Intercepted solar radiation
Method 1	0.28	0.55	0.38
Method 2	0.47	0.51	0.42

Since yields continued to increase with higher rates of P, while ground cover did not, the additional yield cannot be attributed to increased light interception alone. Phosphorus is required for energy transfer in plant cells and when the levels of P in the plant are sub-optimal the transfer of energy absorbed by chlorophyll could be reduced (Marschner, 1986). Hence P rates above 100 kg ha^{-1} may be increasing yield by improving the photosynthetic efficiency or the stress tolerance of the plant (Sale 1973; Gutierrez-Boem and Thomas, 1999). Petiole concentrations of P, while responsive to P rate, were only just reaching sufficient levels at the highest P rates

(Freeman *et al.,* 1998) (Figure 4-34 p 137). Hence, it is likely that sub-optimal tissue levels of P occurred in many of the plots with P 100 kg ha^{-1} or less.

The relative quantities of band applied and soil available P may also influence the development and duration of the canopy. Plants with band applied P develop a canopy earlier (Table 4-7), (Jenkins and Ali, 1999) and begin tuber initiation sooner with a larger number of tubers set (McCollum, 1978). Hence, they have a larger tuber sink than unfertilised plants. During the mid to late growth period the plants' P source shifts from band placed fertiliser P to soil reserves of P (Pursglove and Sanders, 1981). This shift is due to the development of a larger root system which is able to exploit the whole of the available soil volume, hence diluting the P obtained from fertiliser sources (McCollum, 1978). If the soil supply is not sufficient to meet the plants' needs, P is translocated from the canopy to the tubers resulting in the loss of leaf area and the early onset of senescence (McCollum, 1978). This situation does not occur in plants that are P deficient from the onset since the tuber sink is proportionally smaller and the P demand of the tubers does not exceed the plant uptake of P. The reduced tuber production of low P fertiliser plants found by McCollum (1978) reflects inefficiencies in the allocation of assimilates due to a limited P supply rather than a limit on the production of assimilates.

Conversion rates of 0.76 g MJ^{-1} for P sufficient and 0.68 g MJ^{-1} for P deficient plants were obtained from the intercepted radiation modelling. These values are comparable with those of Sale (1973) 0.63-0.80, but much lower than those observed by Allen and Scott (1980) 1.58 g MJ^{-1} for potatoes, or 1.42 g MJ^{-1} for sugar beet (Clover *et al.*, 2001). The low correlation obtained between both the duration of ground cover and the intercepted radiation with dry matter yield indicate that other factors influence dry matter accumulation in potatoes.

The assumption that net assimilation is directly proportional to intercepted solar radiation (Allen and Scott, 1980; Jenkins and Ali, 1999) is questioned by Sale (1973) who preferred a source sink type explanation, where the rate of assimilate transfer to tubers is governed more by tuber demand than by limitations or variations in solar radiation. The two to three week period after the onset of tuber initiation is critical for determining final yield (Milthorpe and Moorby 1967 *cit* in Sale 1973). Hence,

conditions during the early growth of tubers may affect the size of the tuber sink. High temperatures during early tuber growth can delay tuber bulking (Bodlaender 1963 *cit* in Allen and Scott 1980). Potato root growth reaches an optimum at 20-25°C while shoots reach an optimum growth at 30°C (Marschner, 1986) hence higher temperatures may favour shoot growth over root development. During November 2000 the soil temperature at Forthside was 2 °C warmer than the 35 year average of 16.2 °C, which may have reduced the tuber sink size and hence accounted for some of the lower conversion rates.

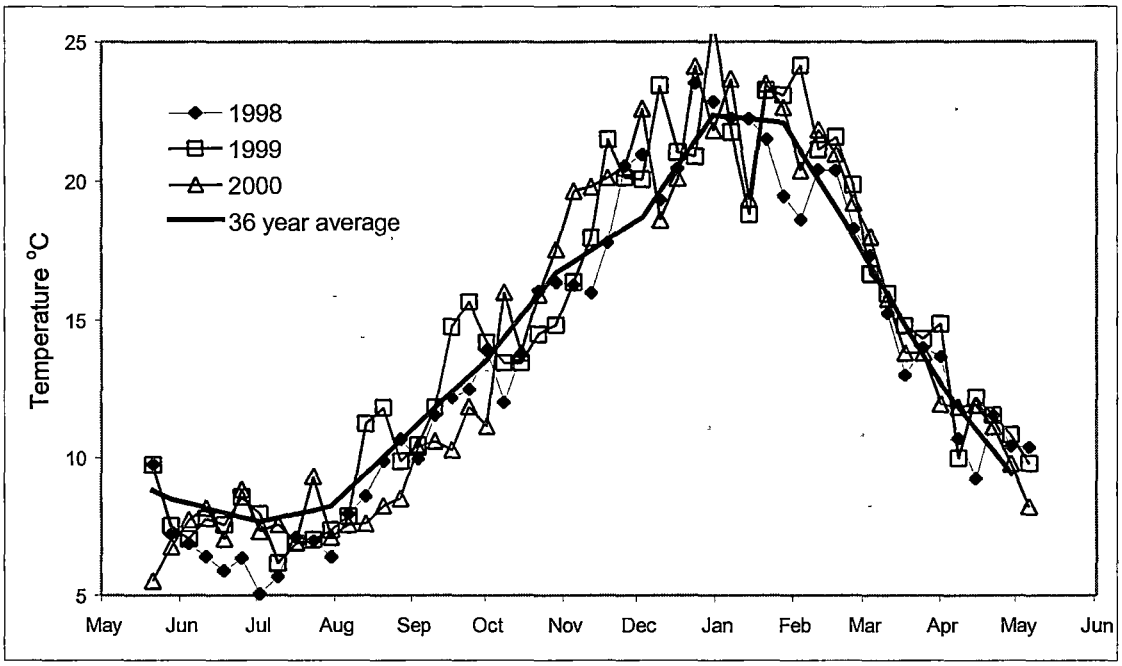


Figure 4-10. Forthside soil temperature at 10 cm depth weekly average from June 1998 to May 2001 and long term 36 year average for Forthside.

Respiration rates increase with increasing temperature (Sale, 1973) and such increases in respiration may offset or exceed any gains in intercepted radiation under high radiation intensities. If there is an upper limit of solar radiation, above which no net increase in photosynthesis occurs, then still higher levels of solar radiation will only increase respiration through raising the plant's temperature and effectively reduce net assimilation. Clover *et al.* (2001) included adjustments for mean saturation deficits that greatly improved the relationship of intercepted radiation and yield of sugar beet, a crop with similar moisture requirements to potatoes (Figure 1-10). Methods that account for the stress levels of plants may further validate this

approach. The addition of phosphorus tends to increase the apparent conversion rate of radiation to dry matter. Such an effect may be due to an increased utilisation of photosynthetic energy or through a higher tolerance to stress of P sufficient plants (Gutierrez-Boem and Thomas, 1999).

Phosphorus deficient Russet Burbank potatoes tend to have smaller, narrower leaves and consequently there may be less light received by the P deficient plants. However, the effect of narrowing the leaflets to 20% of their original width did not cause the ratio of ground cover to LAI in the modelled data to deviate from the established curve (Figure 4-8). Ground cover is an accurate gauge of photosynthetic area even if the leaf morphology has changed. Hence, the decrease in efficiency of conversion for the P deficient plants is likely to be physiologically based rather than as a result of morphological leaflet modifications.

Digital imaging proved satisfactory for detecting differences in the ground cover of a potato crop with different rates of applied phosphorus fertilisers and irrigation treatments. Ground cover differences were apparent during early growth and throughout senescence. However, there is a period between canopy closure and the onset of senescence when changes in LAI and canopy dry matter occur that can not be measured by changes in ground cover.

4.3 Potato canopy irrigation deflection

The shape of the Russet Burbank potato canopy resembles that of an umbrella. Water falling on the upper leaves tends to run to the end of each leaflet from where it can be shed to leaves lower down in the canopy. This process may then repeat with the result of water being shed to the outer edge of the canopy. The immature leaflets at the shoot tips can funnel water towards the stem (Saffigna *et al.,* 1976). There may be a marked difference between the distribution of water falling on bare soil and that occurring below potato canopies. These effects may influence the distribution of roots and their subsequent uptake of fertiliser and soil P reserves.

An increased movement of irrigation water into the soil under the stems and the canopy drip lines of seven week old potato canopies was found by Saffigna *et al.* (1976). However, these effects were reduced in older canopies. Preferential stem

and furrow wetting appear to take place based on soil moisture data from Stieber and Shock (1995). The data from ten week old plants shows more effects of stem and drip line wetting than that of 13 week old plants. Hence, canopy age has an effect in both the net radius of the drip line during early growth and upon the efficiency of the stemflow and dripline effects. The reduction in stem and drip flow of older plants is largely a result of lodging of the stems (Saffigna *et al.,* 1976).

Water flow on tree canopies can be described by the interception and storage of water on leaves, the flow of intercepted water down the stem, and under certain circumstances the outward redirection of water to the dripline (Alva *et al.,* 1999; Xiao *et al.,* 1998). These phenomena have only been sparingly investigated in annual crops. Both stemflow and canopy drip have been implicated in the soil surface distribution of irrigation applied to carrot and potato canopies (Carter *et al.,* 2000; Saffigna *et al.,* 1976). Stem flow in corn was also found to improve the effectiveness of parasitic nematodes applied through overhead irrigation by concentrating the nematodes at the base of the plant (Ellsbury *et al.,* 1996).

The interactions of irrigation water with plant canopies have implications for the utilisation of band placed fertiliser. The effects depend greatly upon the sorptive properties of the soil. A soil that is highly absorptive of water, such as a ferrosol, will be much less influenced by localised inequalities in irrigation than a sandy soil with much lower absorption (Taylor and Ashcroft, 1972). Canopy deflection in potato crops transfers water that would enter the hill to the furrows. Since the hill contains the bulk of the topsoil, with the greatest reserves of residual P and other fertilisers, water deficit in the hill may reduce the potential uptake of P.

4.3.1 Methods

A combination of field data and modelling from a physically based computer model was used to describe the redistribution of intercepted overhead irrigation water by potato canopies. Field measurements of water redistribution were collected from eight week old plants when there were approximately 15-16 leaves per plant. The length of each leaf, the number of leaves around the stem and angle of the leaf to the stem were measured and used as parameters to develop the model. The length, width

and angle of the petiole of leaflets were also measured and these were used to describe leaflet geometry in the model.

The model was based on three principal modes of water redirection by the canopy, (Figure 4-11):

Flow 1: emerging apical leaves slope back towards the stem and transfer all collected water to the stem. The effective water catching length of apical leaves is reduced according to the acuteness of the angle to the stem.

Flow 2: water falling on mature leaves is transferred along the leaflet axis to the tip.

Flow 3: water dripping from the tip of a higher (donor) leaf may fall to a lower (acceptor) leaf and be further transferred to the acceptor leafs tip and so on.

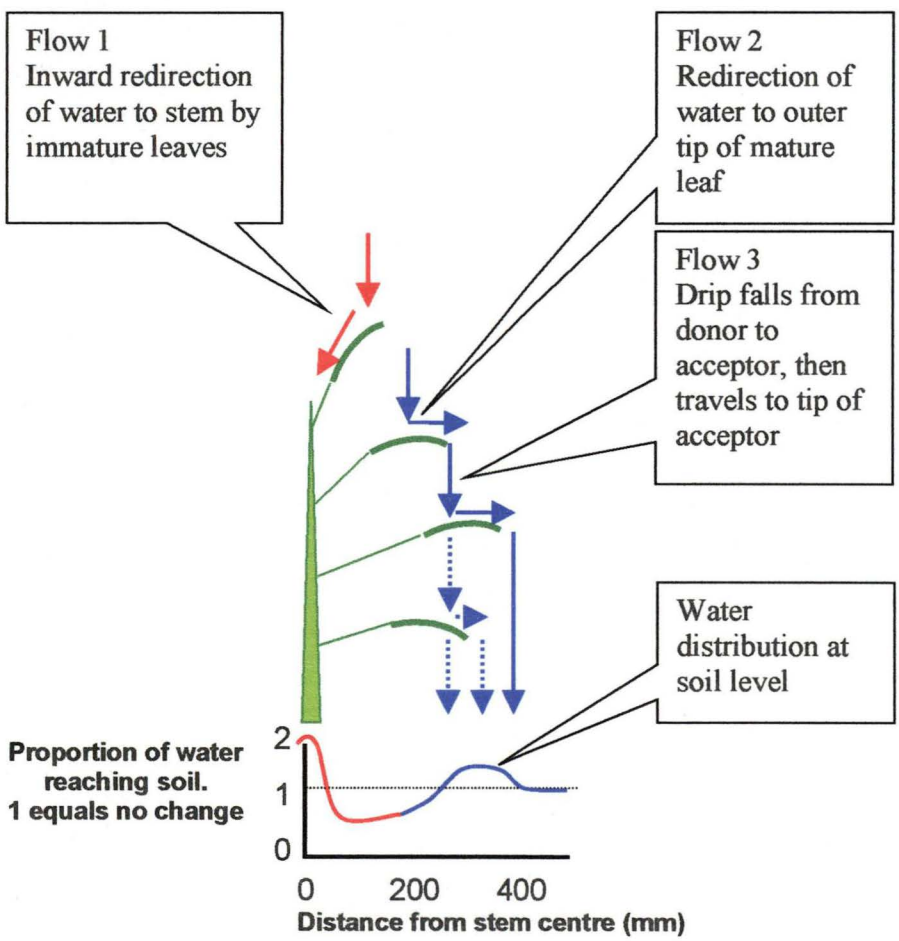


Figure 4-11. Canopy redirection of overhead irrigation water and model construction. Water flows inward to become stem flow (red), outward by running along leaflets to become canopy drip (blue), or does not interact with the canopy.

The model was further modified by a leaf growth function, which sets the leaf size for canopies of between five and twenty leaves so that the effects of canopy age can be included. Both leaf angle and length are influenced by random variation so that each run of the model generates a unique canopy structure. The growth functions were derived from field data.

The geometry of potato canopies contributes to the proportion of canopy drip. Mature leaflets point downwards and away from the stem and thus tend to carry water to the outside edge of the canopy. Immature leaves form a funnel that contributes to stemflow. Every second to third leaf up the stem overlaps so that water on one leaflet may drop onto another lower down (Figure 4-12). At the scale of individual leaflets, leaf hairs may contribute by directing water towards the leaflet tip (Figure 4-12). A raised lip around the perimeter of the leaf may also assist water to be channelled to the tip.

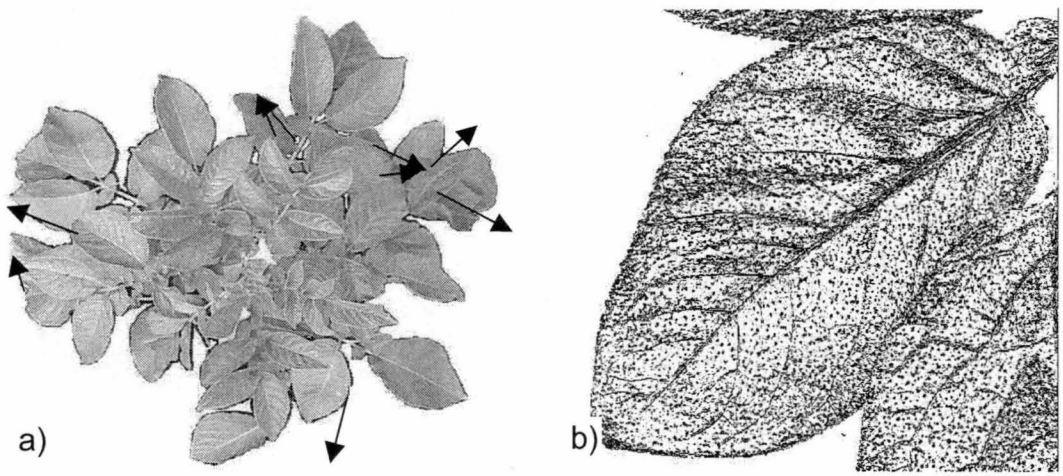


Figure 4-12. a) Potato canopy at 16 leaf stage (eight weeks). The tips of some upper leaves fall within the perimeter of lower leaves and carry drips further towards the edge of the canopy, shown by arrows. b) Pattern of leaf hairs which approximately align with leaf veins. The hairs along the outer edge point towards the tip.

The model works in two modes. The first uses cartesian geometry to plot and analyse interactions between leaflets, principally which leaflets transfer drips to each other and the position of the final drip on the soil surface. The second mode works graphically to determine the catchment area of each leaflet. The individual leaflet catchment areas, including the irrigation shadow beneath the canopy, are then

compiled with the drip history and the final drip position to calculate the quantity of water reaching the soil surface at each position on a 10 mm grid.

Individual leaves are composed of up to 17 leaflets, though cv. Russet Burbank can be adequately described with five to seven leaflets. Each leaflet is specified by its proportion of total leaf length, its branching position on the petiole and the angle that it subtends to the petiole. The values chosen for the model are based on measurements and photographs of leaves from field grown plants. The transfer of water from one leaflet to another is assessed by ascertaining if the leaflet tip of a higher (donor) leaflet falls within the perimeter of a lower order acceptor leaf. If this is true then the drip can fall onto the lower leaf.

The coordinates of each leaflet were used to draw an image of the plant. Each leaflet is represented by an oval that is sequentially coded by a greyscale index from 10-255. The final image is stored as a bitmap image of 800 x 800 pixels with a scale of one pixel per mm (Figure 4-13). The area of each leaflet and the total plant area or irrigation shadow, are calculated in Scion Image®. The results are then compiled in MS Excel using the data for each leaf tip, drip point, and drip transfers that occur. The model output can be displayed as a radial distribution of water around the stem or as the quantity of water received in each cell of a grid over the ground surface.

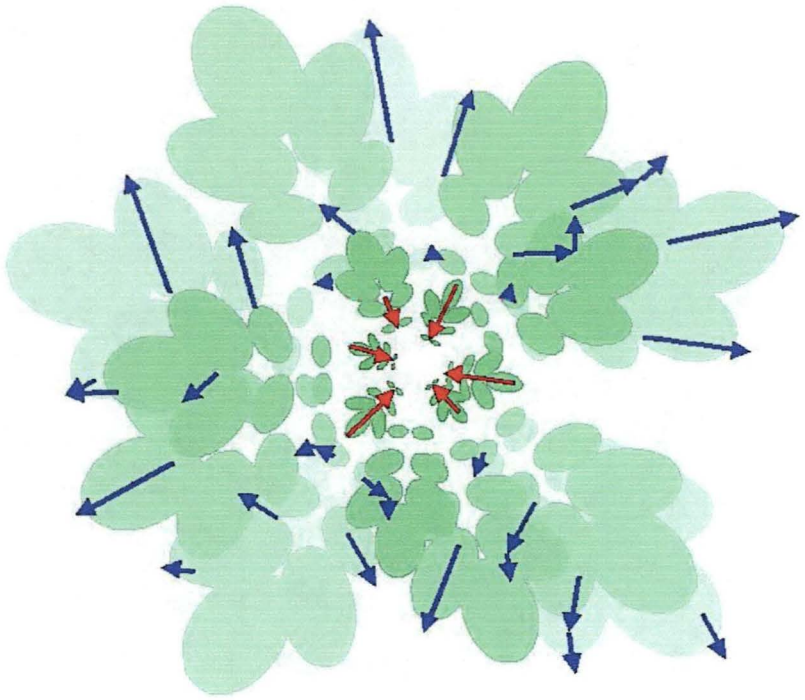


Figure 4-13. Sample model output of water redirection on a twenty leaf plant. Blue arrows indicate canopy drip and show direction of water travelled from tip of upper (donor) leaf to tip of lower (acceptor) leaf. Red arrows indicate stem flow by inner leaves.

The model was validated by two independent field measurements. A selection of eight week old field grown plants were cut off at ground level. The plants were cut early in the morning and measurements were made within 5-15 minutes of cutting. Stem flow, through flow and canopy deflection were measured using a set of concentric rings, from 50 mm to 300 mm radius in 50 mm increments (six rings total), (Figure 4-14). A constant rate of water was applied through a shower rose rotated on an axis approximately one m above the centre of the concentric rings. The shower rose had an increasing number of holes from the centre, four holes, to the outside ring, 32 holes, so that each ring received a constant precipitation rate. The depth of water in each ring was measured after an average application of 50 mm of water. Control readings, taken without plants, were acquired every four to six measurements and were used to obtain a calibration for the apparatus. Cotton threads were used to support the plants in an upright position.

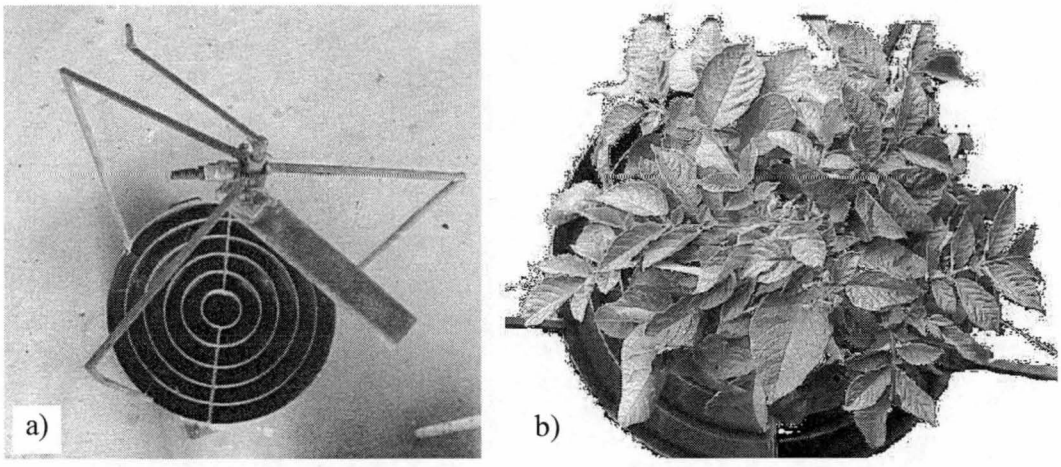


Figure 4-14. a) Device used to measure canopy irrigation redirection. b) Field plant ready for measurement of canopy drip. Concentric rings of the catchment trough can be seen below the canopy.

A ThetaProbe® (ThetaProbe ML2 Delta-T devices) read by a lap top computer using an ADC 10 analog to digital converter (Pico ® Technology Limited), was used to measure the surface soil capacitance below potato canopies immediately after the termination of irrigation. Data is presented as the absolute difference of each reading from the average value. The sample points are on a grid at 50 mm intervals and cover an area of one m^2. This allowed the distribution of actual irrigation water on the soil surface to be mapped.

4.3.2 Results

The field data from 15-16 leaf plants generally falls between that of the 10 and 15 leaf modelled data (Figure 4-15). The stem and through flows of the field plants most closely approximate the 10 leaf plant while the canopy drip, determined by the length of the largest leaf, best fits the 15 leaf plant. The lower stem flow and higher through flow of the field plants suggests that some of the water that falls on to a leaflet does not traverse the full distance to the drip point at the tip. The field plants began to wilt soon after cutting, which would have reduced the ability of the canopy to redirect water. Ideally, the apparatus should be placed around intact field grown plants. However, this proved too difficult in the present study due to the problem of forming watertight seals around the multiple stems of the potato plants.

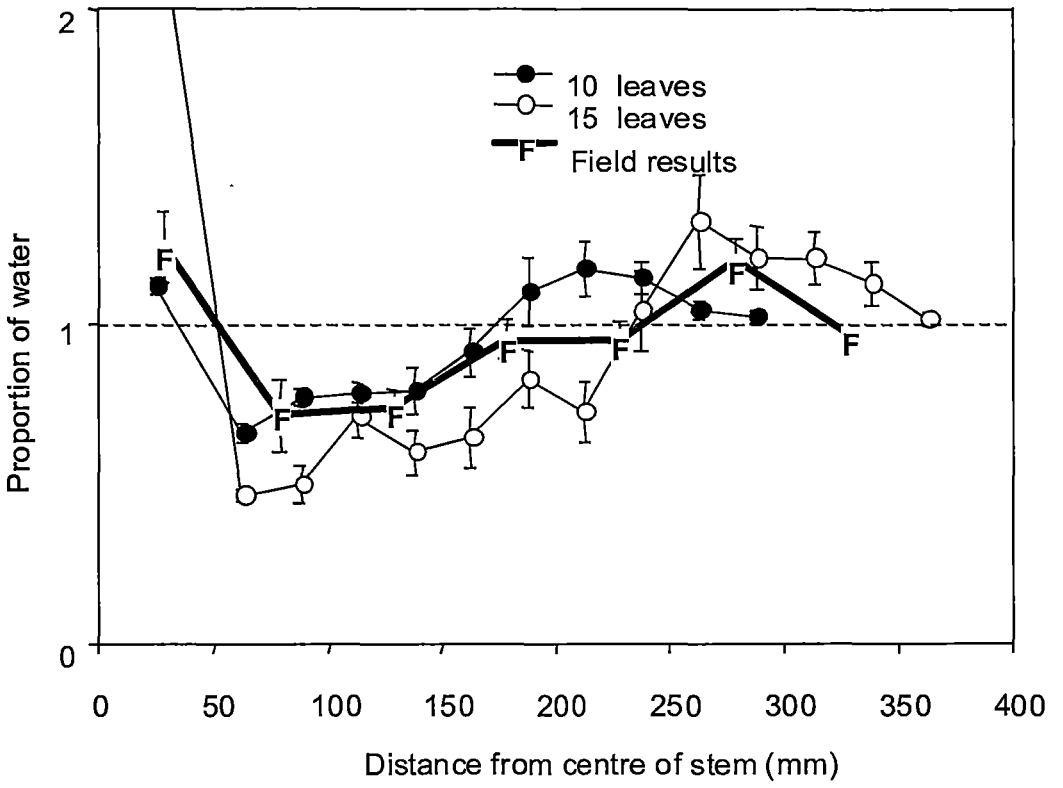


Figure 4-15. Model and field data shown as proportion of water in a radial slice. Field data (F) are from six plants in duplicate at the 15-16 leaf stage.

The model assumes the ideal condition that all water falling on the leaflet proceeds to the drip point. In reality, older mature leaves are convex in shape, which could allow a component of drip from the perimeter. The lower than expected stem flow, seen on the field data, may be due to a smaller effective catchment area of the immature apical leaflets. Some intermediate leaves contribute to both stem and canopy drip flow; the model may be more biased towards stem flow in this situation. The water distribution predicted from two adjacent plants along a hill is shown in Figure 4-16. Water is effectively shed from the region where the two canopies overlap and is removed to the drip line in the furrow.

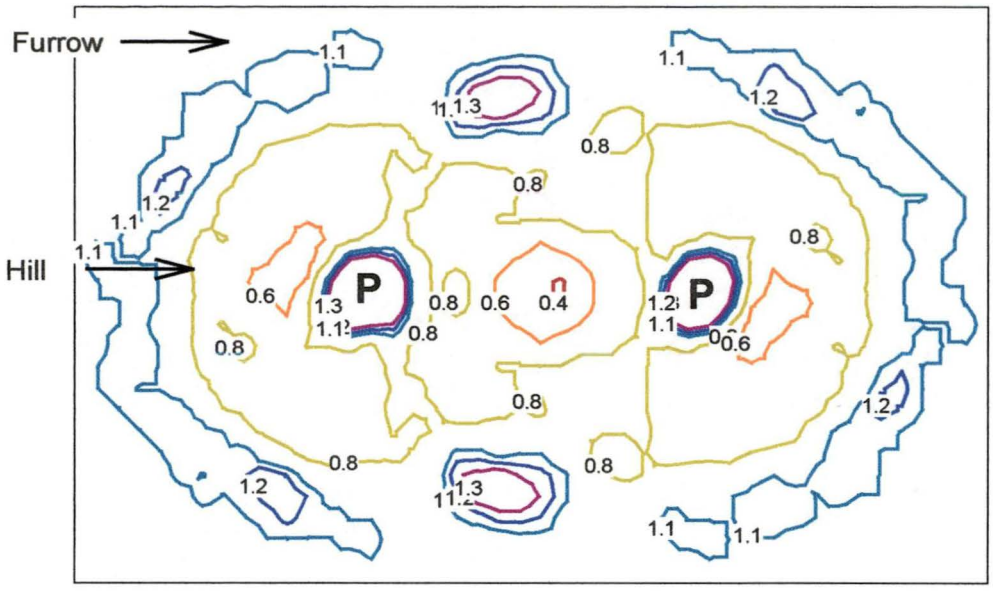


Figure 4-16. Proportion of water reaching the soil surface below two overlapping potato canopies. Plant stems are denoted by "P".

The modelled water distribution pattern was confirmed by field measurements of surface soil capacitance values under recently irrigated potatoes. The relative increase in soil volumetric water content, calculated as the difference from the average dry soil value, is shown in Figure 4-17. There is a marked increase in moisture (positive values represent increased soil moisture) in the furrows while the hills remain dry under sprinkler irrigation. There was no evidence of stem flow from the soil capacitance data; the driest values are obtained from the soil beneath each stem. The soil moisture pattern conforms to that predicted by the model (Figure 4-16) and individual plant measurements (Figure 4-15). Drip irrigation produces the opposite effect. The volumetric water content of the furrows remains unchanged, while that of the hill soil is greatly increased by the three drippers present (Figure 4-17). In both images, the soil on the northern slope is drier than the corresponding southern slope due to increased solar radiation on the northern aspect.

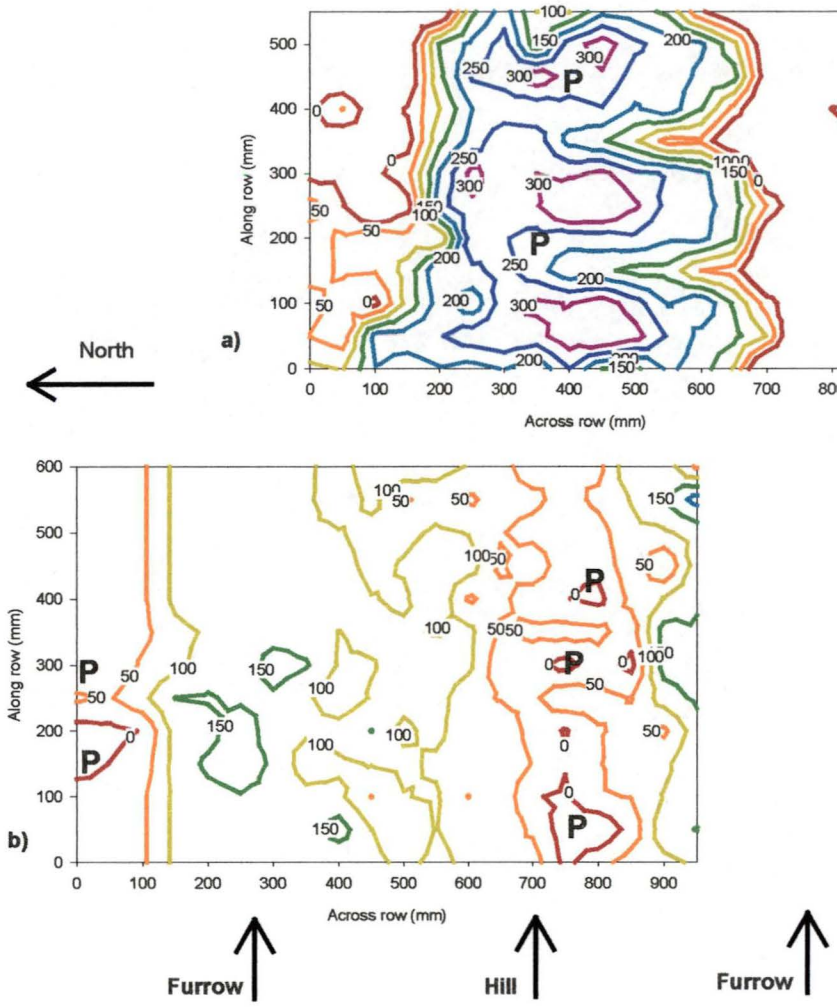


Figure 4-17. Soil capacitance values, uncorrected data, of the surface of potato hills after a) dripper irrigation and b) sprinkler irrigation. Positive values indicate increased volumetric water content. Position of plant stems (P).

The general shape of canopy of the Russet Burbank potato is similar to other commercial potato varieties (Potato Marketing Board, 1965; Canadian Food Inspection Agency, 2002), though early maturing varieties tend to be shorter. The effect of canopy water redirection should be applicable to most commercially grown potato varieties.

4.4 Soil physical properties and implications for root growth

Soil cultivation and compaction affect a range of soil physical properties that can influence root growth (Bishop and Grimes, 1978) and soil water dynamics (Ressler *et al.,* 1998). The moisture content at the time of compaction may affect some or all of these properties. Bulk density, penetration resistance and soil hydraulic conductivity can be readily measured from intact soil cores collected in the field. The following experiments were intended to ascertain whether soil bulk density alone determines a soil's strength and hydraulic properties or whether the moisture content at the time of compaction has an influence. The relationship of soil bulk density to soil penetration resistance and saturated hydraulic conductivity will be useful for interpreting root distribution and soil moisture relationships.

4.4.1 Methods

Intact soil cores were collected in 42 mm diameter by 20 mm deep stainless steel rings during March 1999 at Paloona and in December 2000 at Forthside. Sampling at Paloona was from the furrows and the hill centres at 100 mm depth increments to a total depth of 400 mm below the top of the hill. At Forthside, samples were collected from furrows, the sides of hills, half way between the furrow and hill centre, and hill centres at 100 mm depth increments from 50 mm to 450 mm below the top of the hill.

Repacked cores were prepared in the laboratory to compare the effects of soil moisture levels prior to compaction. Soil from a bulk store of Forthside ferrosol soil held outside was collected from regions that were air dry, moist, and wet. The corresponding soil moistures were 16%, 26% and 30% gravimetric respectively. To produce repacked cores two 42 mm diameter by 20 mm deep stainless steel rings were placed one on top of the other, with a piece of filter paper underneath the lower ring. The rings were filled with soil and compressed in a hand-operated press. After compression, the top ring was removed and the press piston lifted off and the remaining exposed soil was cut off with a knife flush with the top of the lower ring. The soil directly below the piston experiences more compressive force than lower regions that may adversely affect the hydraulic conductivity if the surface layer has become sealed.

Soil penetration strength was measured at various gravimetric water contents while the soils dried down after saturation. Soil penetration resistance was measured with a hand held flat tipped penetrometer of 3.18 mm diameter. The penetrometer was previously calibrated against electronic scales.

Selected field and laboratory samples were tested for saturated hydraulic conductivity. The samples were placed on a 1 mm aperture sieve suspended over a funnel. Water was fed manually through a wash bottle to the top of the sample so that a film of water remained across the surface and no air entry occurred. Once steady state flow was reached a container was placed under the funnel and the through flow collected for a period of 30 seconds to 10 minutes depending on the flow rate. Bulk densities were determined on each core after all other measurements had been made by oven drying at 105°C.

4.4.2 Results

4.4.2.1 Soil bulk density

Soil bulk density increases with greater soil depth and in the region under the trafficked furrows. The hilled soil has a bulk density of 1.0 Mg m^{-3} or less (Figure 4-18). Uncultivated subsoil and wheel compacted topsoil has a bulk density ranging from 1.0-1.2 Mg m^{-3}. The bulk densities at Paloona are slightly higher than at Forthside but the overall pattern is the same. However, bulk density alone is not a good indicator of the strength of a soil in relation to root growth. Penetration resistance is a more accurate indicator of a soil's strength. Field results from the Forthside 2000 trial of soil penetration strength in potato mounds are shown in Figure 4-31 p 130.

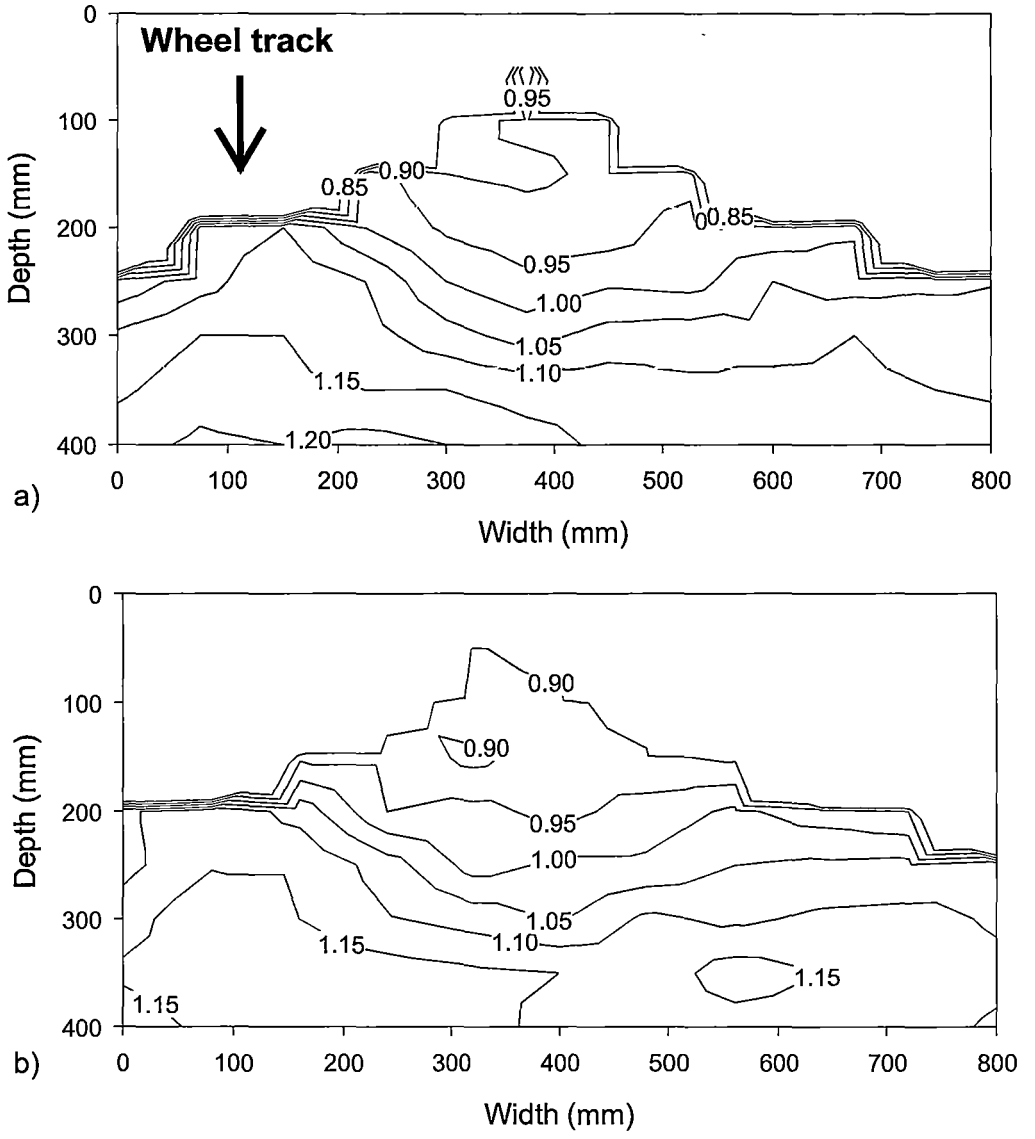


Figure 4-18. Soil bulk density Mg m^{-3}, a) Paloona 1998, b) Forthside 2000.

4.4.2.2 Penetration resistance

The combined effects of increasing bulk density and lowering soil moisture content increase the penetration resistance of the soils (Figure 4-19). Soils with low bulk densities (below 1.05 Mg m^{-3}) reached maximum penetration strength between gravimetric moisture contents of 18-25%. There is a decrease in penetration resistance of the low bulk density soils at moisture contents below 15%. Soils that had a higher bulk density (greater than 1.05 Mg m^{-3}) continued to increase in penetration resistance at progressively lower water contents. There is an indication that theses soils may also reach a maximum penetration resistance somewhere below

10% gravimetric soil moisture content. However, such low soil moisture contents would not occur under field conditions when a potato crop is being grown. The heavily compacted soil, with a bulk density of 1.3 Mg m^{-3}, reaches an extremely high penetration resistance (13.8 MPa) after drying to 13% moisture content.

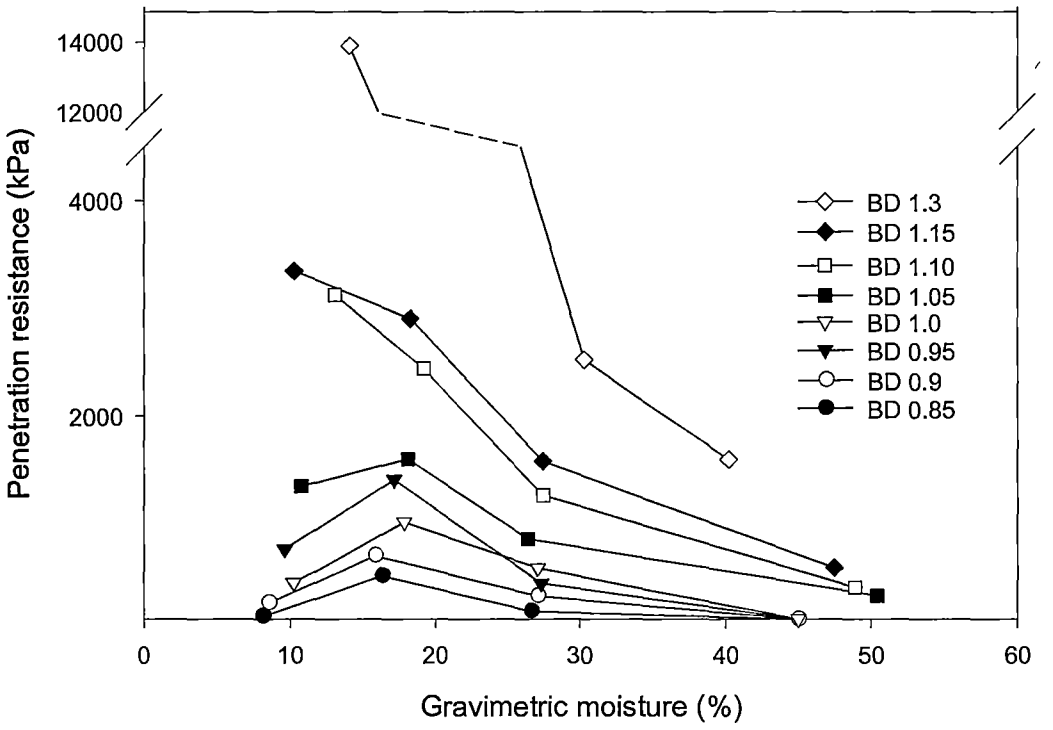


Figure 4-19. Penetration resis tance as a function of gravimetric water content and soil bulk density (Mg m^{-3}).

In a preliminary study with a loose soil (BD < 0.95 Mg m^{-3}) a similar rise then fall in soil penetration resistance with decreasing soil moisture content was clearly evident (Figure 4-20). A bulk density of 1.05-1.10 Mg m^{-3} appears to be a boundary between increasing penetration resistances in higher bulk density soils after further drying and a reduction in penetration resistance in lower bulk density soils after drying. Individual aggregates could be readily seen in soils of bulk density 1.05 Mg m^{-3} and less, whereas in soils with higher bulk densities the aggregates were deformed and in close contact with each other resulting in a massive soil appearance. The behaviour of water menisci within these two different aggregate arrangements may be influencing the penetration resistances.

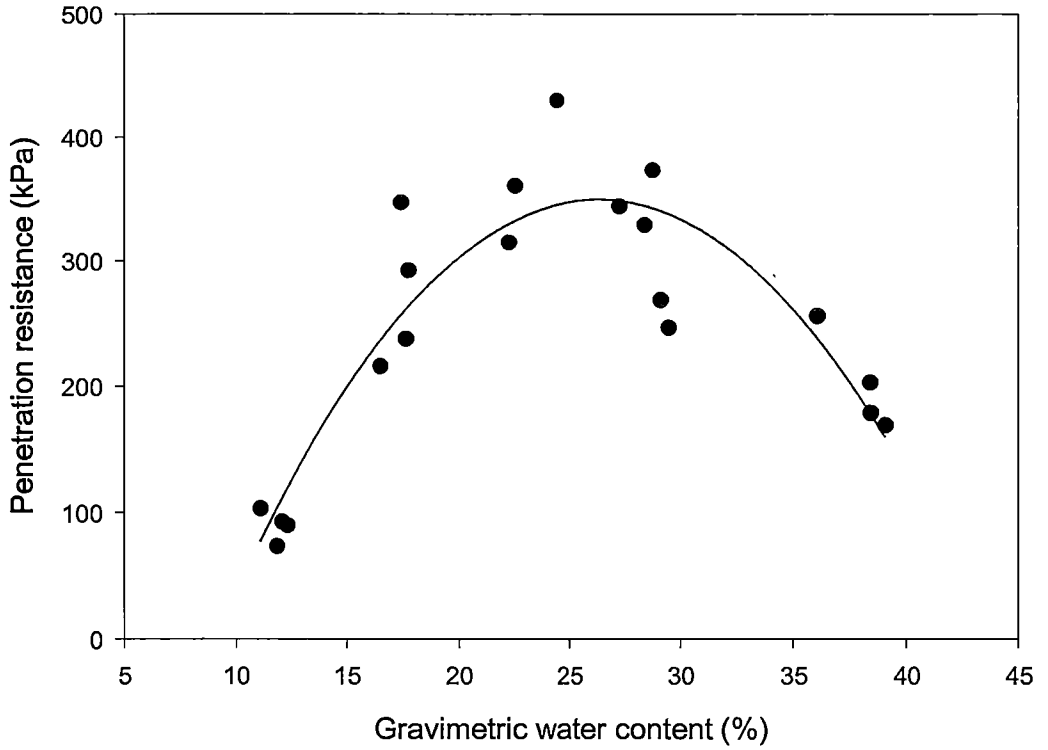


Figure 4-20. Penetration resistance as a function of gravimetric water content of a soil of low bulk density < 0.95 Mg m^{-3}. Taken from a preliminary experiment.

4.4.2.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity was clearly affected by soil bulk density (Figure 4-21). The moisture contents prior to compaction had no affect on hydraulic conductivity (data not shown). Bulk densities greater than 1.2 Mg m^{-3} may limit saturated hydraulic conductivity, though only at very high rates of irrigation or rainfall (more than 100mm h^{-1}). Even extremely high bulk densities (in excess of 1.3 Mg m^{-3}) do not restrict saturated hydraulic conductivity at normal irrigation rates. However, surface-sealing arising from tractor wheel slip or implement smearing may reduce hydraulic conductivity to below irrigation rates under field conditions (Davies and Finney 1973).

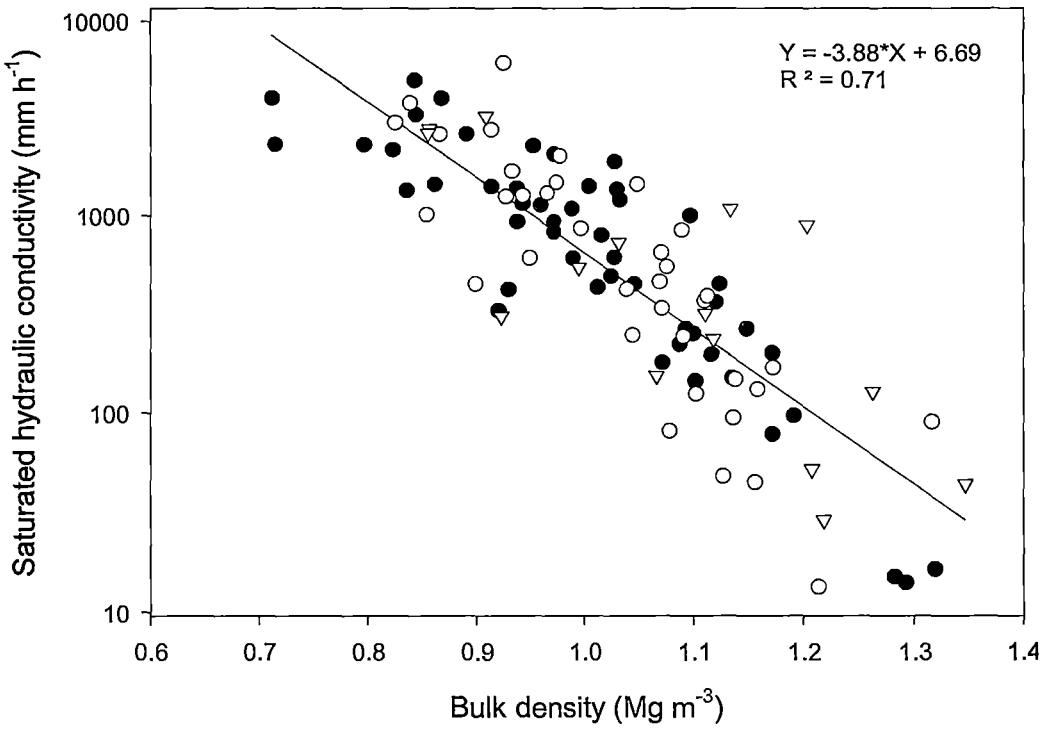


Figure 4-21. Saturated hydraulic conductivity as a function of soil bulk density, data from field sites, Paloona 1999 (○) and Forthside 2001 (▽) and laboratory experiments (●).

The higher conductivity values of some field collected cores at bulk density greater than 1.2 Mg m^{-3} may be due to the presence of biopores, which are not present in the repacked cores. Since ferrosols are highly structured soils, the contribution from biopores has less effect on saturated hydraulic conductivity than in soils with poorer inherent structure.

4.5 Potato root growth in glasshouse trials

The distribution of roots strongly influences the ability of the plant to acquire nutrients and water. The pattern of root growth may be matched to other soil properties such as bulk density and penetration resistance to gain a better understanding of how root growth is affected by these soil properties (Bishop and Grimes, 1978; Tardieu, 1988). Soil moisture can affect the growth of roots (Rab and Willatt, 1987) and their acquisition of nutrients (Baerug and Steenberg, 1971). An understanding of how soil moisture affects root growth will be useful for interpreting the effects of soil conditions on the root growth of field grown potatoes.

Two glasshouse trials and a laboratory experiment were conducted to assess the effects of soil conditions on potato root growth. The laboratory trial investigated the effects of soil matric potential on root elongation. The first glasshouse trial was established to gauge the effects of two different soil moisture regimes (wet and dry soil at two depths) with mild subsoil compaction on the root growth of potatoes. This experiment was also used to develop root imaging methods that could be used later with field grown potatoes. The second glasshouse trial examined the extent of lateral root growth of potato roots in unhilled soil.

4.5.1 Methods

4.5.1.1 The effect of soil matric potential on root growth

A laboratory experiment was conducted to investigate the effects of soil water matric potential on root growth. Sprouted cv. Russet Burbank potato shoots were planted into 500 ml aluminium trays with 500 g loose air dry soil that had been previously moistened with sufficient water to reach –60, -160, -290 kPa soil moisture tensions. The soil had a bulk density <0.95 Mg m-3. The trays were kept inside sealed plastic bags to prevent desiccation and grown indoors at 20 °C beside a north facing window. Supplementary illumination was given by fluorescent grow tubes with a 16 hour day period. Shoot weight and root length were recorded from whole plants removed over a period of twelve days.

4.5.1.2 The effect of soil moisture and mild sub soil compaction on root distribution

Soil moisture and strength can both influence the distribution of potato roots (Bishop and Grimes, 1978; Rab and Willatt, 1987). A glasshouse experiment was set up to acquire digital images of potato roots from soils with different moisture levels. Potato plants were grown in red ferrosol moistened to two water contents, dry (-100 kPa) and moist (-10 kPa). The soil treatments were divided into topsoil, (0-10 cm) and subsoil (10-20 cm), giving a factorial combination of four treatments, wet/wet, wet/dry, dry/wet and dry/dry (Figure 4-22). The four treatments were contained in an aluminium tray 2 m long by 1 m wide by 250 mm deep in four rows. Each row was 250 mm wide and separated from the other rows by sheets of plastic to prevent

water movement between adjacent treatments. The subsoil was lightly compacted to simulate the increased soil bulk density found below the banded fertilisers under field conditions (Figure 4-18 p 114). N, P and K were placed in a double band at rates equating to 200, 100, 300 kg ha^{-1} respectively.

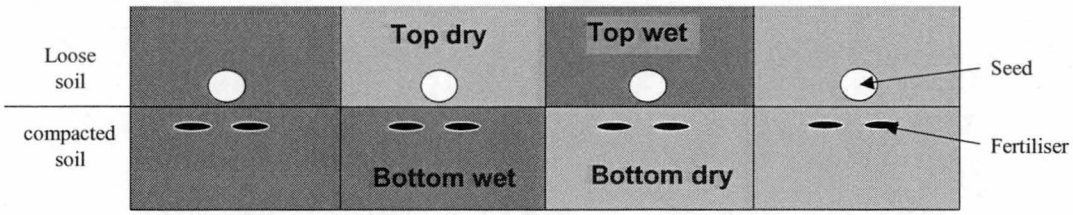


Figure 4-22. Soil treatments, seed and fertiliser placement for the soil moisture and strength experiment.

The soil surrounding three plants was sequentially sectioned at 15 mm intervals at four and eight weeks after planting. The soil was gently washed away with a stream of water to expose approximately 5 mm of root. Digital images (10-12 per plant) were then taken of the exposed roots from each plant using a Sony Mavica MVC-FD91e digital camera. The thresholded images (black and white) were overlayed and averaged. The shoots were retained for dry matter yields. A final dry matter cut only was taken after twelve weeks. Soil moisture samples were collected before excavating the roots. The trial was not watered over the twelve week period.

All images were digitally analysed on Scion Image ® software. Areas of root in the images were separated from areas of soil by manually thresholding the green component of the red/green/blue bitmap image (Figure 4-23). For a more detailed explanation of techniques see Section 4.2.1, Figure 4-5 p 90. Shoots and tubers when present were manually edited. A macro program was written to automate opening, selecting the green component, and saving the resulting thresholded image. This allowed 20-50 images to be processed in a few minutes. Manual editing of the images was required to remove stems, tubers and other unwanted parts from the images; this was the most time consuming part of the process.

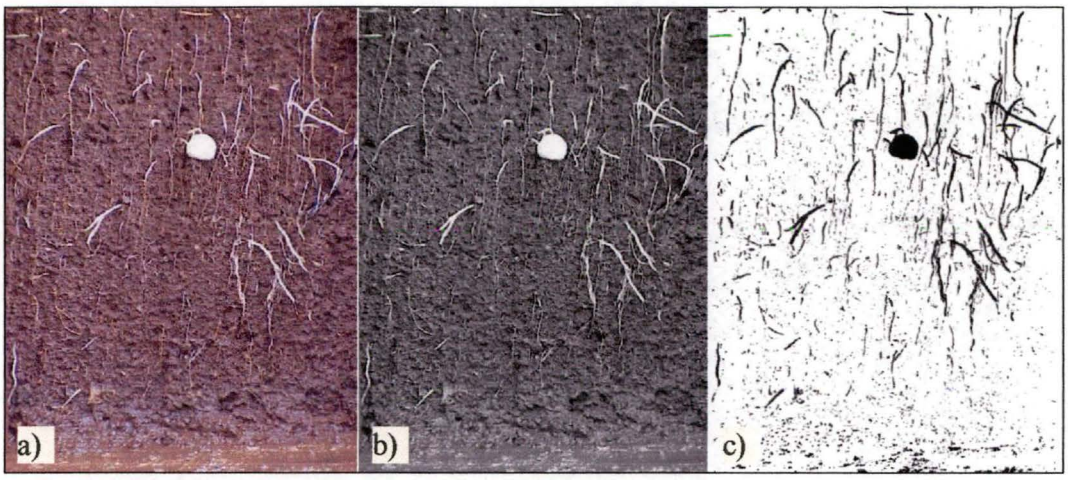


Figure 4-23. Root image separation process, a) original image, b) green component of red/green/blue bitmap image, c) final binary image.

4.5.1.3 The root distribution of potatoes grown without hilling

Potato plants were grown in the same tray used for the soil moisture and strength experiment (Section 4.5.1.2 p 118) except that only one row of twelve plants was grown along the middle of the tray and the soil was left unhilled. The first six plants were excavated after four weeks. The remaining six were excavated after 38 days. Root exposure and digital image analysis were by the same method as the previous experiment (Section 4.5.1.2 p 118). Root densities were obtained by overlaying all the images for a given treatment and averaging them. The averages were then converted to points on a grid by calculating the average value for each grid area. When scaled appropriately this gave a measurement of root area per unit area of soil.

4.5.2 Results

4.5.2.1 The effect of soil matric potential on root growth

Soil matric potential strongly influenced the root length of potato plants (Figure 4-24). Matric potentials > pF 2.2 (-160 kPa) significantly reduced root length. A 10% reduction in relative root elongation occurs with a decrease of –13 kPa matric potential from pF 1.8 (–60 kPa) to pF 1.9 (–73 kPa). Extrapolating the relative root growth rates indicates root growth may cease entirely below matric potentials of pF 2.9 (–800 kPa), assuming there is a linear trend, though the effect of moisture levels below -160 kPa was not tested.

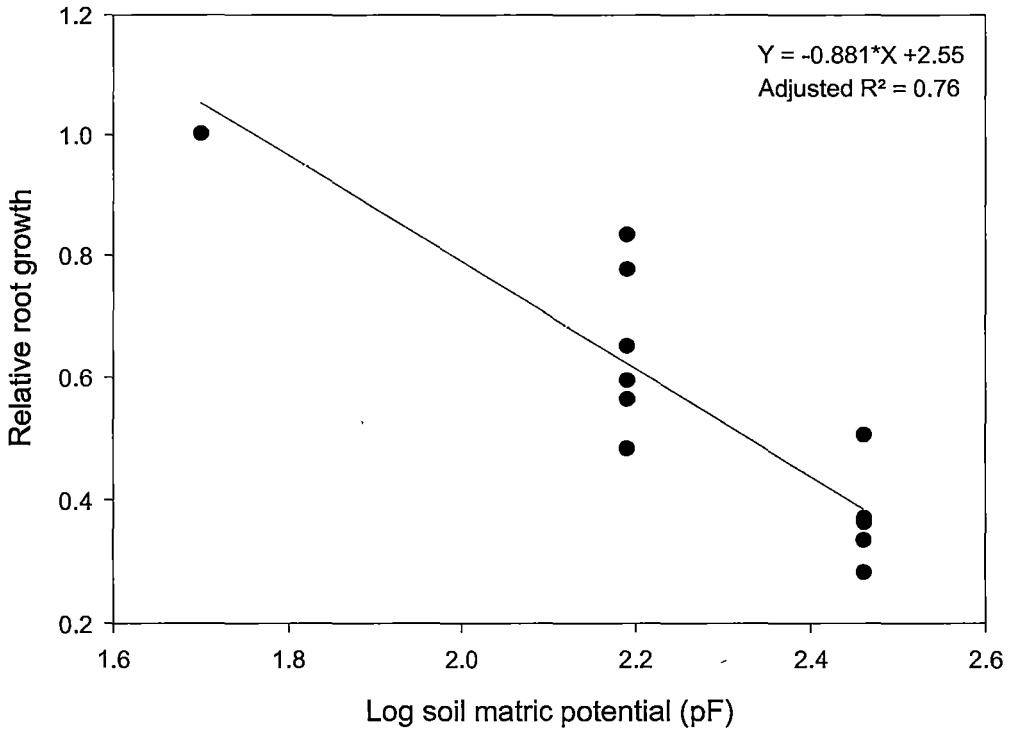


Figure 4-24. Relative root length, as a proportion of root growth at pF 1.7, of potato plants at three moisture regimes.

Since the soil bulk density was below 0.95 Mg m^{-3}, penetration resistance could not reach levels that could inhibit root growth (Figure 4-19 p 115). The observed effect on root length is due to soil desiccation only.

4.5.2.2 The effect of soil moisture and mild sub soil compaction on root distribution

Initial gravimetric soil moisture levels were 41% for the "wet" soil and 29% for the "dry" soil. These correspond to -7 and -85 kPa matric potentials respectively. After four weeks, the treatments that had at least one section of moist soil (wet/wet, dry/wet and wet/dry) had a similar pattern of root growth (Figure 4-25). There is a marked lack of root growth under the dry/dry treatment. Fertiliser was placed as a band in the lower third of the image, seen as a line of black dots in the dry/dry image (Figure 4-25, d). The roots from all the treatments with at least one wet section have reached the fertiliser, while those from the dry/dry treatment are only just beginning to grow near the fertilised region. The wet/wet treatment appears to have the largest root system.

A similar pattern of root growth occurred after eight weeks (Figure 4-26); the roots of the dry/dry treatment had still not grown into the fertilised soil. Secondary roots, seen as the thin vertical lines, are more abundant on the wet treatments after eight weeks, but there is some secondary root growth on the dry/dry treatment. A similar proliferation of secondary roots after four weeks of growth was found in the pot trial with liquid MAP (Figure 3-7 p 71).

Table 4-9. Shoot dry matter yields (g) of potatoes grown in soil of different moisture regimes.

		four weeks	eight weeks	twelve weeks
Topsoil	Dry	0.78	1.11	5.26
	Wet	0.73	1.60	3.93
	F prob	NS	0.005	NS
Subsoil	Dry	0.78	1.40	3.64
	Wet	0.74	1.31	5.54
	F prob	NS	NS	0.031

Shoot weight showed no significant difference after the first four weeks of growth (Table 4-9) even though there were differences in root development. By eight weeks, treatments with wet topsoil had a higher shoot weight than treatments with dry topsoil. After twelve weeks, the treatments with wet subsoil had the largest shoot dry weight, though there was considerable variation. The plants were not watered for the duration of the trial, and by twelve weeks were showing signs of water stress.

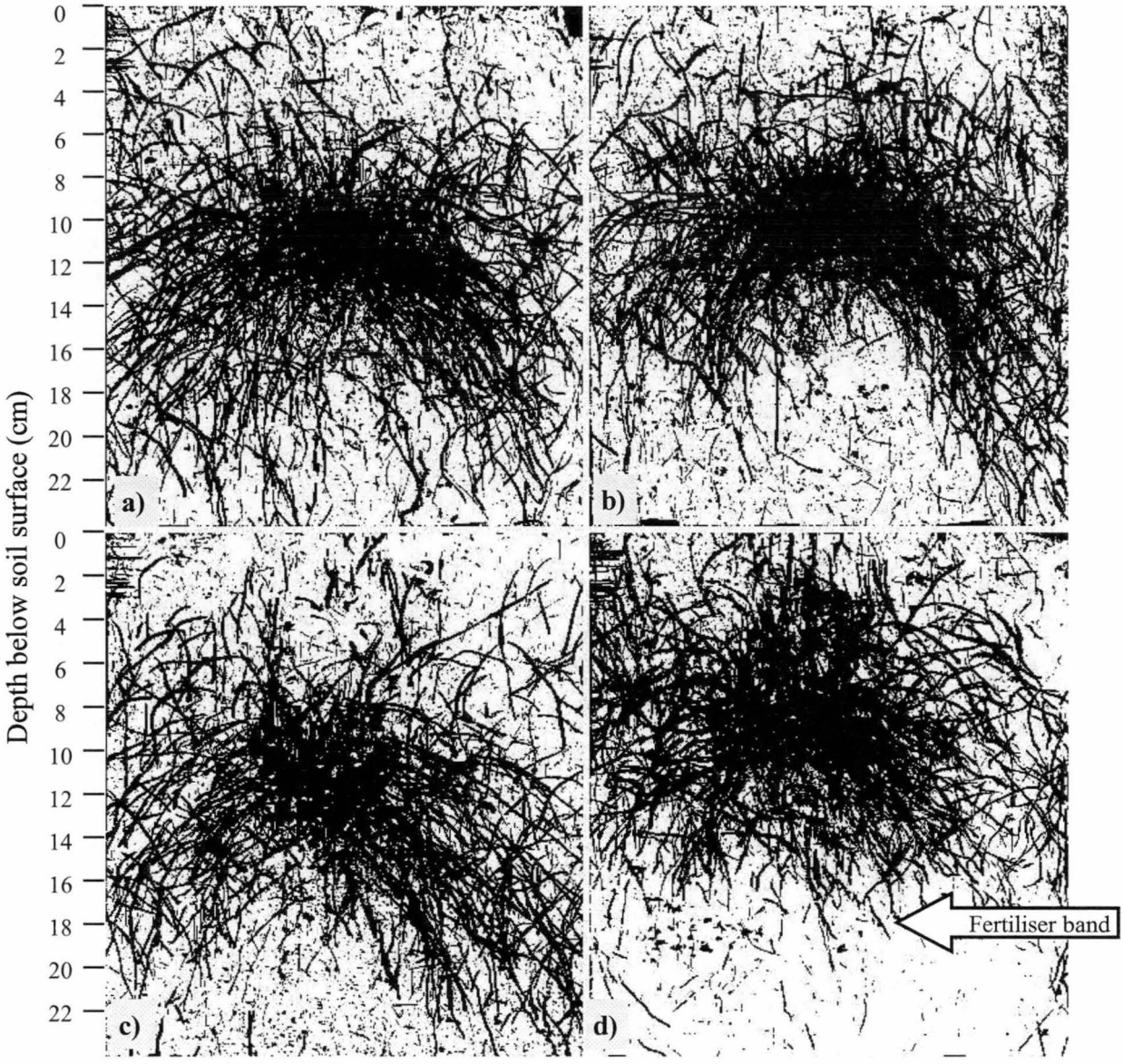


Figure 4-25. Potato root systems at four weeks after planting. a) Wet/wet, b) wet/dry, c) dry/wet and d) dry/dry. Small spots along the bottom quarter in the dry/dry root image are residues from band placed phosphorus fertilisers. Images show an area of 220 mm x 240 mm.

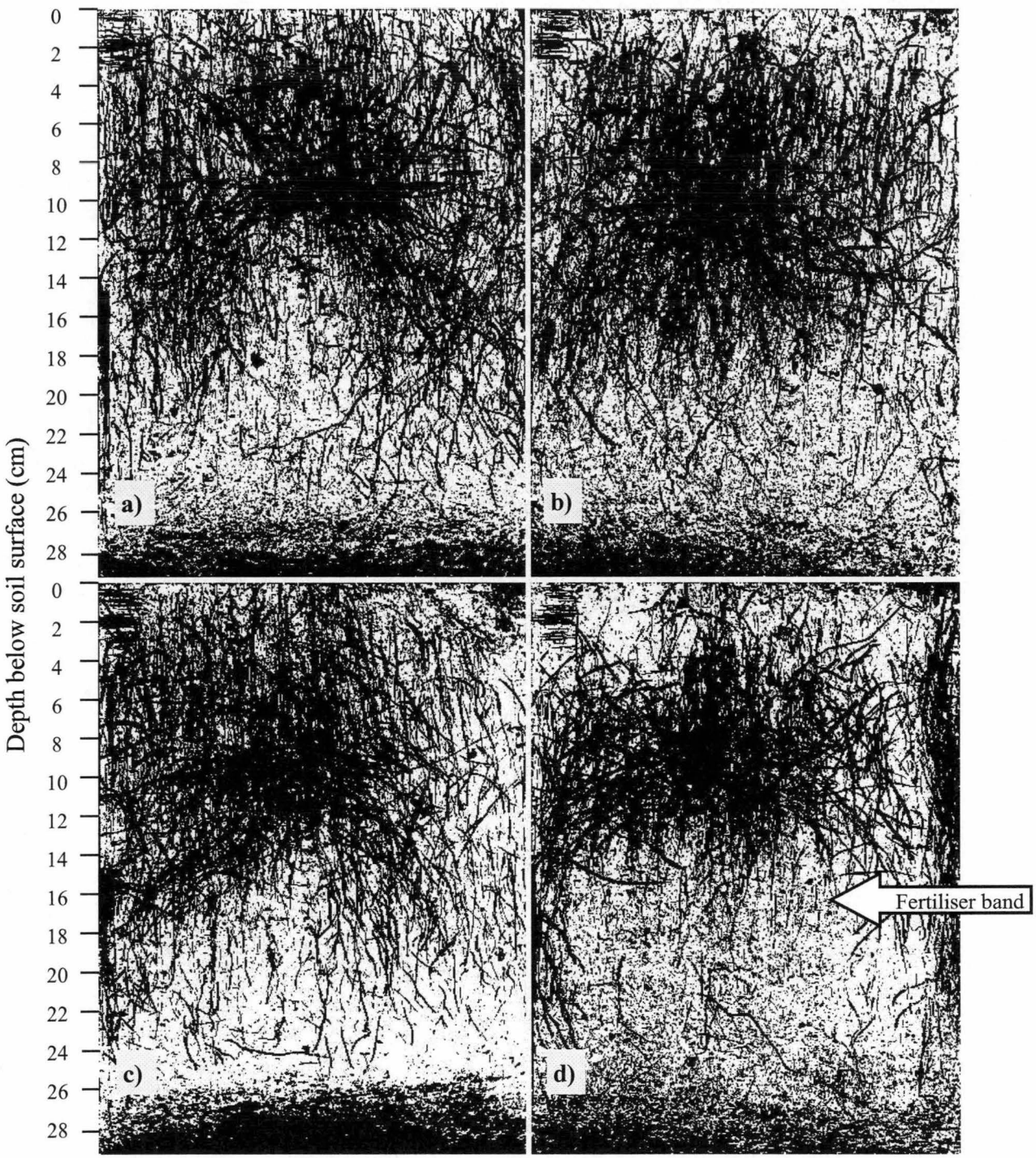


Figure 4-26. Potato root systems at eight weeks after planting. a) Wet/wet, b) wet/dry, c) dry/wet and d) dry/dry. Secondary roots can be seen as thin (0.1 mm diameter) vertical roots. Images show an area of 220 mm x 290 mm.

4.5.2.3 The root distribution of potatoes grown without hilling

The deflection of sprinkler irrigation water away from the hill soil, as is indicated by the canopy deflection results (Figure 4-16 p 110, Figure 4-17 p 111), may affect the uptake of P from the hill soil by reducing the quantity of water reaching the soil in the hill. There may also be implications for water use efficiency since there are likely to be fewer roots growing in the furrows where most of the water is deflected. The roots of unhilled potatoes grow beyond the drip line of the canopy (Figure 4-27) in both the 28 and 38 day old plants. The position of the drip line is indicated by the edge of grey bars, which represent the extent of canopy growth. The growth of roots under the drip line enables the potatoes to utilise water deflected by the canopy.

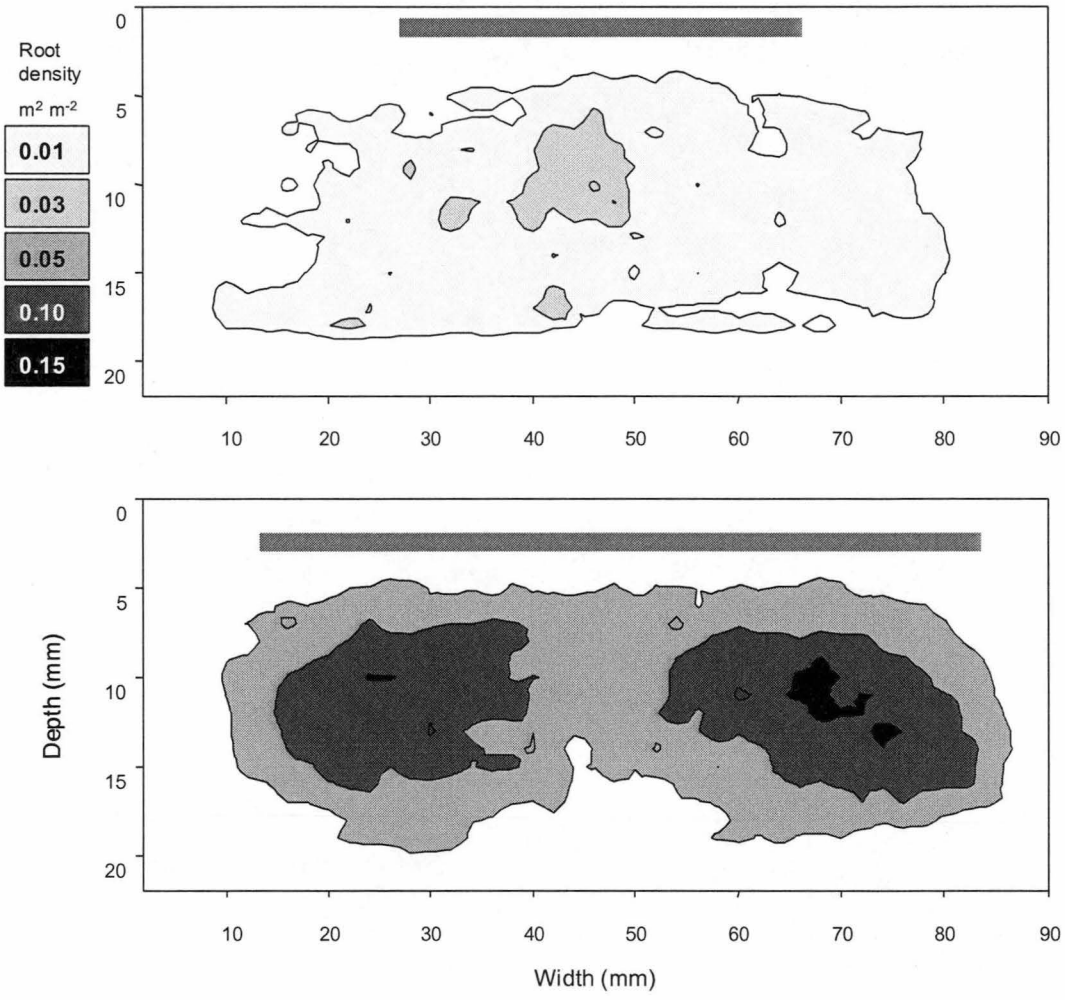


Figure 4-27. Potato root densities m^2 m^{-2} of plants grown without hilling. Top: root density at 28 days. Bottom: root density at 38 days. Grey bars represent canopy width, 400 mm on day 28 and 700mm on day 38.

4.6 Potato root growth in field trials

The distribution of potato roots was observed at various stages of plant development in the field trials. The growth of the early roots, from one to five weeks old, is presented in Section 2.2, Figure 2-5 p 50. The results from field grown plants from the trial on irrigation with granular starter P are presented here.

4.6.1 Methods

Vertical sections of potato hills, four rows wide by 0.6 m deep, were exposed in one of each of the sprinkler, dripper and unhilled treatments of the 2000 field trial site (Section 4.1.1 p 78). The potato roots were exposed by cutting a smooth vertical section and then picking at the soil with a table fork to expose 5-10 mm of root. Slide photographs were taken of the finished sections and these were later scanned and analysed by the same process used for Section 4.5.1.2 p 118.

Penetrometer readings were collected with an Agridry Rimik cone penetrometer (CP20) with an ultrasound depth recorder. Transects 1.9 m wide (two rows) and 600 mm deep with readings taken at every 100 mm interval were obtained. A 2 m x 150 mm plank with 20 mm diameter holes drilled every 100 mm was placed across the top of two mounds to establish a constant base level and to maintain a regular interval between subsequent readings. Depth zero was the top of the mounds and the lateral distance between readings was 100 mm. Becher, (1994) recommends the minimum distance between adjacent penetration readings should not be less than five times the cone diameter otherwise compaction from the previous reading will influence the following measurement. This value equates to 65 mm for the 13 mm diameter tip of the CP20, which is well below the 100 mm distance used.

Penetrometer readings were collected before plants reached 50% emergence and again after the crop began to lodge during early senescence. The canopy was too high for reliable readings to be taken between these times without damaging the plants. At each time interval and for each irrigation treatment, five penetrometer transects were collected along the same pair of rows at 5 m intervals. The sequence was advanced 0.3m in the next period. The differences between previous and present readings were calculated by a pair wise subtraction; that is, the previous section from

position one was subtracted from the present reading at position one (0.3 m ahead) and likewise for the remaining four replicates.

4.6.2 Results

The effects of severe compaction can be seen by the absence of root growth into the compacted soil, below the line, in Figure 4-28, from plants grown at Paloona 1998. In young plants grown at Forthside in 2000 the root growth is centred around the seed tuber (Figure 4-29). By eleven weeks, the roots have reached most regions of the hilled soil (Figure 4-29). There was no large difference in the root distribution between dripper and sprinkler irrigated plants (Figure 4-30). However, there appears to be an increase in the root density in the 400-500 mm depth of the dripper treatment which is also evident in images of the dripper irrigated potato roots from eleven week old plants (Figure 4-29). The roots from the sprinkler irrigated crop stop growing at about the depth of the conventionally banded fertiliser, approximately 350mm below the top of the hill. A similar pattern of root growth occurred under the dry/dry treatment of the glasshouse trial on mild subsoil compaction and root growth (Figure 4-25 p 123, Figure 4-26 p 124) where dry compacted subsoil inhibited root growth.

Figure 4-28. Potato root growth in headlands at Paloona 1998. Dashed line shows extent of compacted soil. Left furrow has been wheel compacted.

There is a distinct reduction in root growth under the trafficked left-hand furrow compared to the untrafficked furrow (Figure 4-30). This difference was most pronounced in the unhilled treatment where root growth occurred throughout the untrafficked furrows. The root density in compacted soil has been decreased.

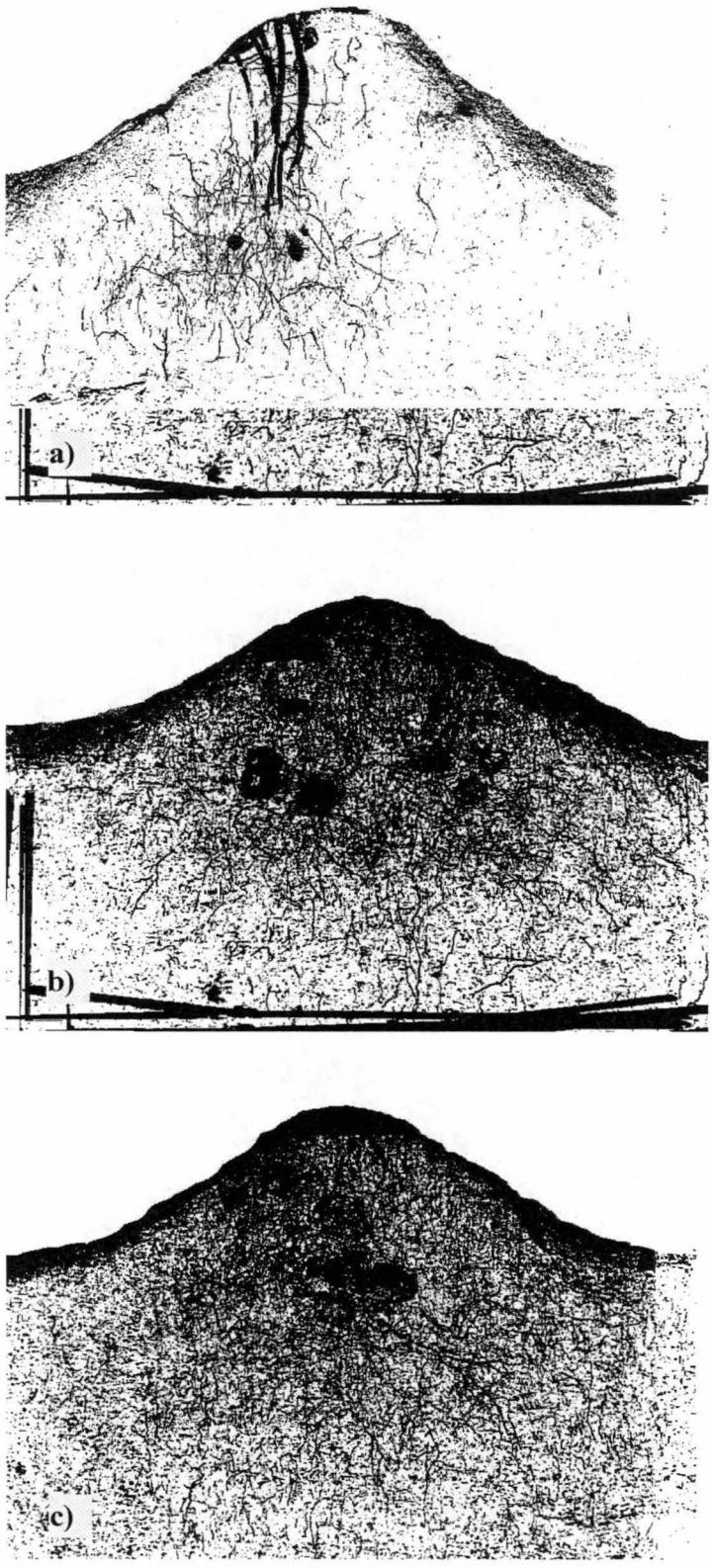


Figure 4-29. Root distribution of field grown potatoes grown under different irrigation methods. a) Sprinklers 12/12/00 (7 weeks), b) sprinklers 9/01/01 (11 weeks), c) dripper 10/01/01 (11 weeks). Pictures show an area of 800 x 600 mm, height of hill is 510 mm.

The images in Figure 4-30 show only the larger roots, >0.5mm, mostly primary and secondary roots. This indicates the structure and extent of the root system but minor localised proliferations are not shown. A close up image from the sprinkler irrigated crop is shown in Figure 5-1 where root proliferation in the conventional band can be readily seen, but there is no root proliferation in the starter band position.

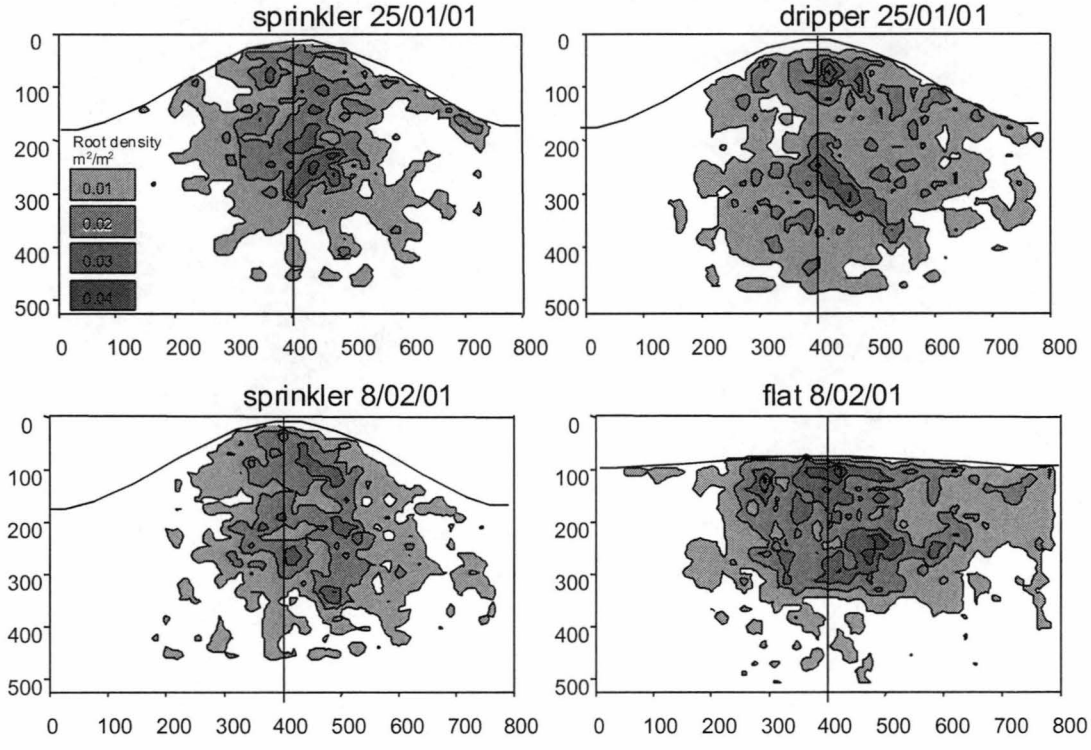


Figure 4-30. Root distribution of field grown potatoes grown under different irrigation and cultivation methods.

The root distributions closely follow the soil penetration resistance (Figure 4-31) and soil bulk density (Figure 4-18). Most root growth occurs in soil of less than 1 MPa (purple region in Figure 4-31) or bulk densities of less than 1.10 Mg m^{-3}. Soil strengths in the trafficked furrows increased to 2-3 MPa (green bars in middle image) after a short period of drying. Since potato roots are unable to grow into soil of 2-3 MPa resistance (Bishop and Grimes, 1978) the region below the plough layer (yellow-green band in Figure 4-31) and the compacted furrows would be inaccessible to roots. Similar patterns of soil compaction were observed by Bishop and Grimes (1978); DeRuijter *et al.* (1996) and Sojka and Busscher (1988) in potato crops. A shallow winged ripper may be effective at loosening compacted furrow soil.

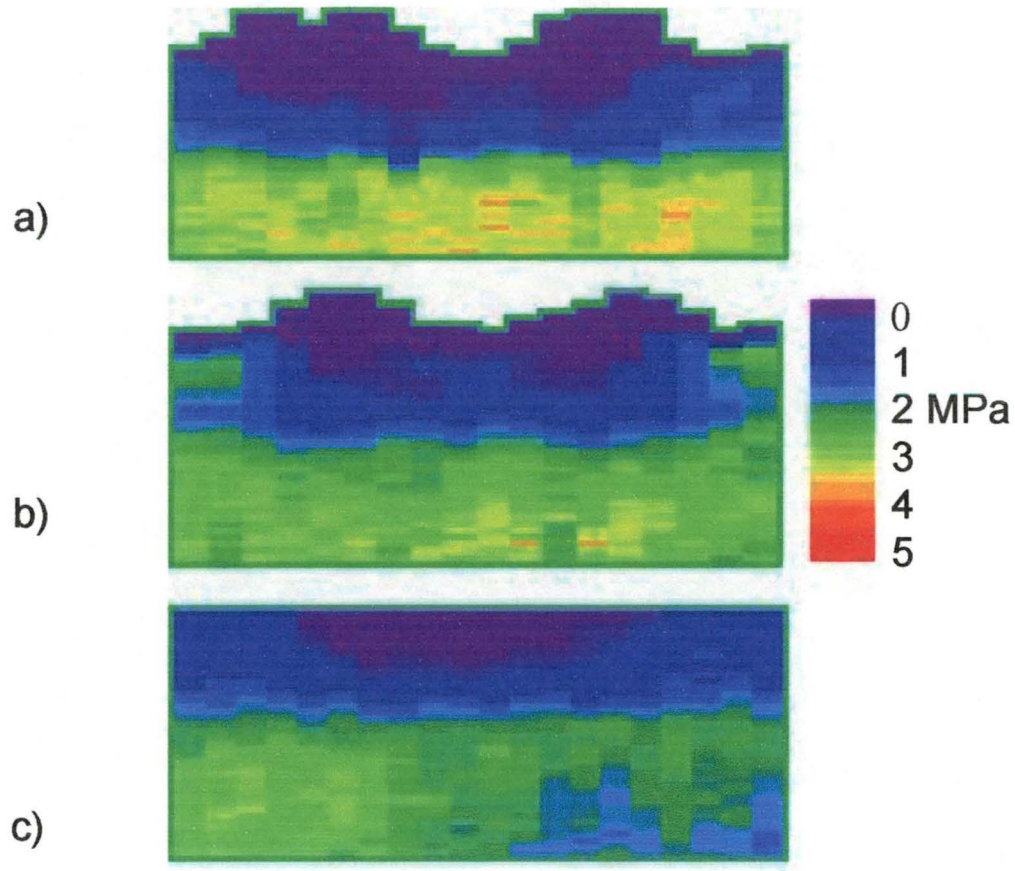


Figure 4-31. Soil penetration resistance under two crop rows with trafficked furrows on the outside edges. a) Normal moisture, b) same hills but drier, c) unhilled cultivation treatment.

Soil matric tension and volumetric water content were measured during the trial; however, the data did not provide sufficient spatial or temporal resolution to detect the distribution of water in the soil. There was greater variation in the moisture contents of the hill soil than lower soil depths or the furrow soil. Root densities were greatest in the hill soil and the greater moisture variation could be due to a higher transpirational demand (Stalham and Allen, 2001).

Some assumptions can be made about the likely movement of water. The initial flow of water into uniformly dry soil is essentially independent of gravity and is instead controlled by the high absorptive properties of dry soil (Taylor and Ashcroft, 1972). When the wetting front contacts moist soil, water can drain more rapidly due to the increase in hydraulic conductivity. An underlying moist region can then siphon off water that would otherwise have redistributed to the drier upper horizons (Taylor and Ashcroft, 1972). The furrows of the sprinkler irrigated crop maintained a water tension close to field capacity (-10 kPa) Figure 4-33. It is possible that deep drainage

was occurring through the furrows of the sprinkler irrigated potatoes, though there was no direct evidence of through flow.

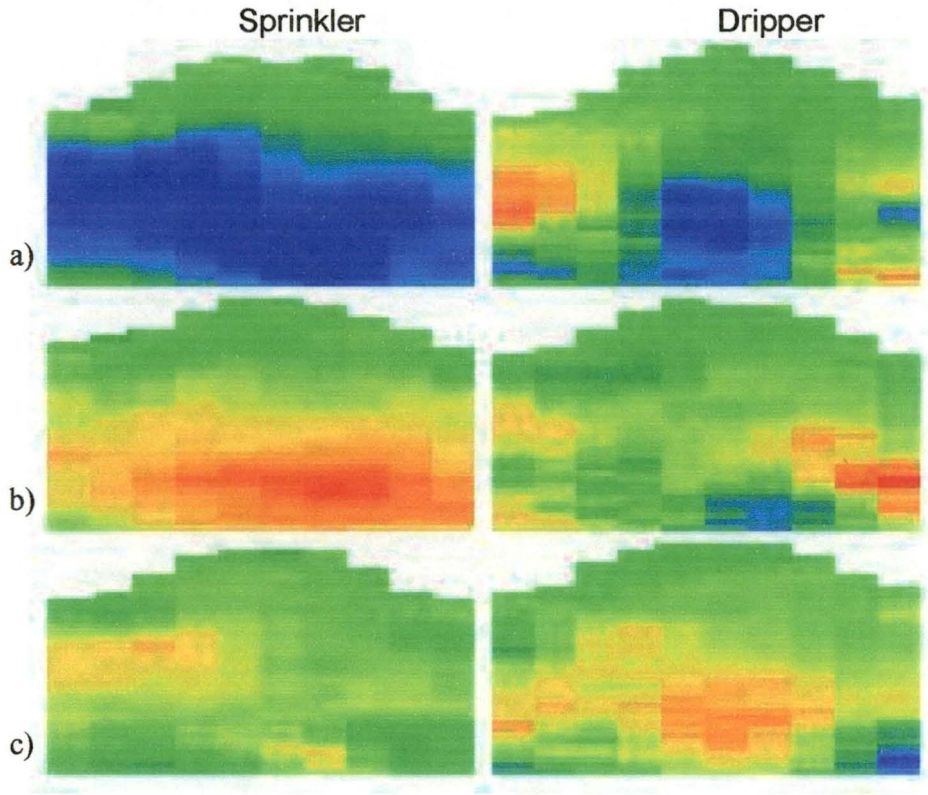


Figure 4-32. Relative penetration resistance differences, left sprinkler irrigation, right dripper irrigation. a) Immediately following irrigation, b) redistribution after three days (sprinkler) and two days (dripper), c) redistribution after seven days (sprinkler) and four days (dripper). Sprinkler irrigation covers a period of seven days after irrigation and dripper irrigation four days after irrigation.

Limited information on the soil moisture patterns was obtained from the penetrometer data. The relative difference between subsequent penetration resistance readings, one to three days apart, is shown in Figure 4-32. Since the soil bulk density was constant between each penetrometer reading, the differences are due to variation in soil moisture (Figure 4-19 p 115). The sprinkler irrigation shows a uniform wetting of the soil and subsequent drying or drainage of the water in the region under the hills. In the final period, four to seven days after irrigation, hardening of the compacted furrow soil is evident (compacted furrow is on left). The drip-irrigated section shows simultaneous wetting of the hill soil and drying of soil in the upper part of the furrows. There appears to be some redistribution of water to the

lower soil below the furrows. In the second time period, after two days, there is drying of the soil 300-400mm below the furrows. Water movement below the root zone is also apparent, which would contribute to nitrate leaching (Figure 4-4 p 88). The final period, days two to three, shows the soil drying in the lower root zone.

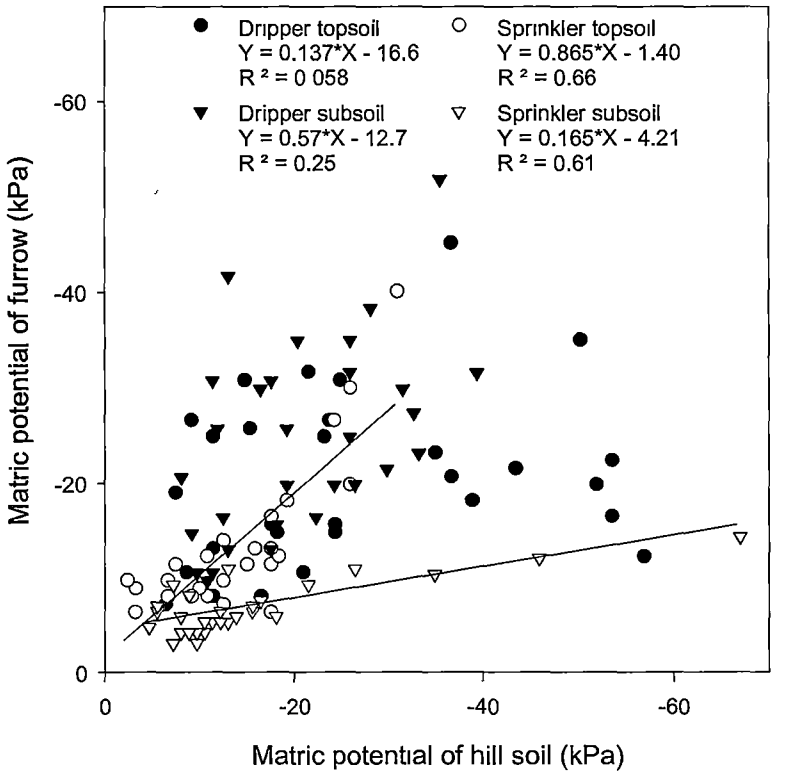


Figure 4-33. Correlation of matric potentials between hill and furrow soil of dripper and sprinkler irrigation at two depths. Topsoil comparison is between tensiometers in the hill at 375 mm and furrow at 250 mm. Subsoil comparison is between tensiometers in the hill at 500 mm and furrow at 375 mm. Fitted lines are for sprinkler irrigation data only.

The ratios of matric potentials of the hill to furrow soils are closely related in the sprinkler irrigated crop (Figure 4-33). This is to be expected since the sprinkler irrigation water was applied uniformly to both the hill and furrow soil. In the topsoil under sprinkler irrigation the matric potentials give a ratio close to unity, (0.865). The ratio in the subsoil is much lower; hence, while the subsoil in the hill dries readily there is only a slight drying of the subsoil of the furrows. Under sprinkler irrigation the furrow subsoil never reaches a matric potential below -10 kPa. This difference is probably due to the transpirational loss of water from the hill subsoil.

The furrow subsoil under drippers on most occasions maintains a matric potential below -20 kPa. The ratio of matric potentials in the drip irrigated crop is more variable. Ideally, the furrow soil should not be moistened under drip irrigation and this is the case on most occasions. However, there are several times when the ratio of matric potentials of the drippers is the same as the sprinkler irrigated crop. This occurs when too much water has been applied through the drippers.

Sprinkler irrigation is applied over the whole soil surface, but the roots tend to be concentrated in the hills (Figure 4-30). There is a greater risk of deep percolation of the irrigation water through the furrows. This is particularly so in the trafficked furrows where virtually no root growth occurs. The uptake of residual soil P is probably less affected than irrigation water since the topsoil (with the bulk of the residual P) is located in the hill. Hence, the zone of highest root activity occurs in the soil with the greatest amount of residual phosphorus which is desirable for the acquisition of residual P.

4.7 Analysis of P responses on all trial sites

The typical yield response of potatoes to P is characterised by an initial sharp increase in yield from P applications up to 50-100 kg P ha^{-1} followed by a gradual increase or no response to higher P rates (Hegney *et al.,* 1989; Stalham and Allen 2001). P toxicity rarely occurs on ferrosol soils and maximum yields in responsive sites are found from the highest rates of applied P (Freeman *et al.,* 1998; Sparrow *et al.*, 1992; Hegney *et al.,* 1989). The gross margins from processing potatoes are high so that the expense of P fertiliser applications up to 95-99% maximum yield can usually be recovered by the marginal yield increases. Potato crops remove between 10-25 kg P ha^{-1}, yet P applications for 95% maximum yield are usually ten times higher than the crop removal of P. This results in a large surplus of P after potato cropping. On ferrosols most of the surplus P is fixed in immobile forms where it becomes part of the soil pool of P available for subsequent crops (Holford and Cullis, 1985).

Potatoes grown on ferrosols are usually responsive to P applications above 100kg P ha^{-1} (Freeman *et al.,* 1998; Sparrow *et al.,* 1992; Pitt, 1984) depending on the soil

available P (Table 1-3). Potato P response was assessed at all sites and critical petiole P concentrations for phosphorus responses are suggested.

4.7.1 Methods

Soils were collected from each trial block and analysed prior to planting at all sites. During the Forthside 1999 trial additional soil samples (one from each plot) were collected during the senescence phase of the crop. This data was used to correlate soil properties with observed differences in plant senescence. Grid sampling was again used prior to planting at Forthside 2000.

Available P and K were measured by 0.5 M $NaHCO_3$ extractable P and K Colwell (16 hour shake) and analysed by the automated colour method for P method 9B2 and K method 18A1 (Rayment and Higginson, 1992). Soil organic matter was measured by Walkley & Black wet oxidation with potassium dichromate, method 6A1 (Rayment and Higginson, 1992). Phosphorus sorption curves were determined by the manual colour method of Rayment and Higginson, (1992), method 9J1. Equilibrium phosphorus concentration (EPC) is an estimate of the soil P concentration, when no P has been added, and is obtained by extrapolating the phosphorus sorption curve to zero. Phosphate buffering capacity (PBC) is the slope of P adsorbed (mg kg^{-1})/log (equilibrium concentration (P μg L^{-1})) (Rayment and Higginson, 1992). PBC O&S is the slope of the phosphate buffer curve between P equilibrium concentrations of P 0.25 and 0.35 mg L^{-1} (Ozanne and Shaw, 1968). Phosphorus adsorption index (PSI 150) is the quantity of P adsorbed at a given EPC, in this case P 150 μg L^{-1} (Rayment and Higginson, 1992) method 9I1.

A regression of criticle petiole P concentrations against tuber yield was calculated using the equation $Y = A + B * X^C$. Critial P concentrations were obtained at both the 90% and 95% maximum yield levels. Petioles were collected from plants at the 5-10 mm tuber stage at Forthside 1999 or 10-20 mm tuber stage at the other 3 sites. The same equation model was used to calculate tuber yield in response to conventional band P applications.

4.7.2 Results

Soil available P was low for all sites except Forthside 1999, in which values were moderate (Table 4-10). However, it was at Forthside 1999 that the highest response to phosphorus rate was found (Table 4-11). Phosphate sorption properties were measured only at the first year's trial sites. The Paloona site had a substantially lower phosphate buffer capacity (PBC) than the Forthside soil, though still within the range of values for ferrosols given by Freeman *et al.* (1998) and higher than the median ferrosol value stated by Burkitt *et al.* (2001). Phosphorus sorption was not measured on soil from the other Forthside sites; however, it should be similar to the value from the site at Forthside in 1998. Soil potassium levels were moderate in all years. The petiole K levels were sufficient at all sites other than Forthside 1999 where they were low to deficient (Chapman *et al.*, 1992) (Table 3-5 p 66). This was the site with the lowest available K levels.

Table 4-10. Soil chemical properties (0-10 cm) for the four field trial sites.

Soil property	Paloona 1998	Forthside 1998	Forthside 1999	Forthside 2000
Colwell P (mg kg^{-1})	16	33	85	43
Colwell K (mg kg^{-1})	-	351	271	344
pH water	5.4	5.9	6.5	-
Salinity (dS m^{-1})	45	81	73	-
Organic carbon (%)	1.9	2.5	3.7	3.3
PBC O&S	55.1	93.8		
PBC	272	465		
PSI 150	68	73		
EPC (µg P l^{-1})	43	50		

Refer to Section 4.7.1: PBC Phosphate Buffer Capacity, PSI Phosphate Sorption Index, EPC Equilibrium Phosphorus Concentration.

The estimates proposed here of critical petiole P concentrations of P 0.3-0.35% (Table 4-11) are lower than those suggested elsewhere for Russet Burbank grown on ferrosols. Sparrow *et al.* (1992) recommended a range of P 0.35-0.4% while Freeman *et al.* (1998) suggested a range of P 0.45-0.57% for Russet Burbank potatoes grown on ferrosols. The predicted P rates for 90 and 95% maximum yield are likewise comparable with Sparrow *et al.* (1992) but lower than Freeman *et al.* (1998). The total P recovery of the two crops where tuber P was measured ranged from 12-22 kg P which equates to 0.30-0.35 kg P for each tonne of fresh weight crop.

All sites were responsive to conventional band applied phosphorus. Yield increases ranged from 15-20% (Table 4-11, Figure 4-34). At all sites there was an increase in tuber number but these increases were in the marketable size categories (75-450 g). Higher conventionally banded phosphorus rates increased both the total yield and the proportion of marketable yield.

Table 4-11. Yield increase, estimated petiole P concentrations and fertiliser P rates for 90% and 95% maximum yield at a maximum P rate of 240-300 kg P ha^{-1}.

		Paloona 1998	Forthside 1998	Forthside 1999	Forthside 2000
P0/Pmax		0.86	0.85	0.79	0.80
Critical petiole P (%)	90%	0.31	0.28	0.27	0.25
	95%	0.35	0.34	0.30	0.27
plant stage		tubers 10-20 mm	tubers 10-20 mm	tubers 0-5 mm	tubers 10-20 mm
P fertiliser rate (kg ha^{-1})	90%	27	50	36	47
	95%	118	147	125	147
P max		240	240	300	300
P removed in crop			14.8-22.2 kg		12.3-18.4 kg
Equation parameters for effects of fertiliser P rate on tuber yield					
A		48.1	65.7	46.6	57.1
B		1.03	0.98	1.78	0.61
C		0.388	0.468	0.329	0.508
Adj R^2		0.66	0.76	0.92	0.85

Equation used to fit regressions was $Y = A + B * P^C$

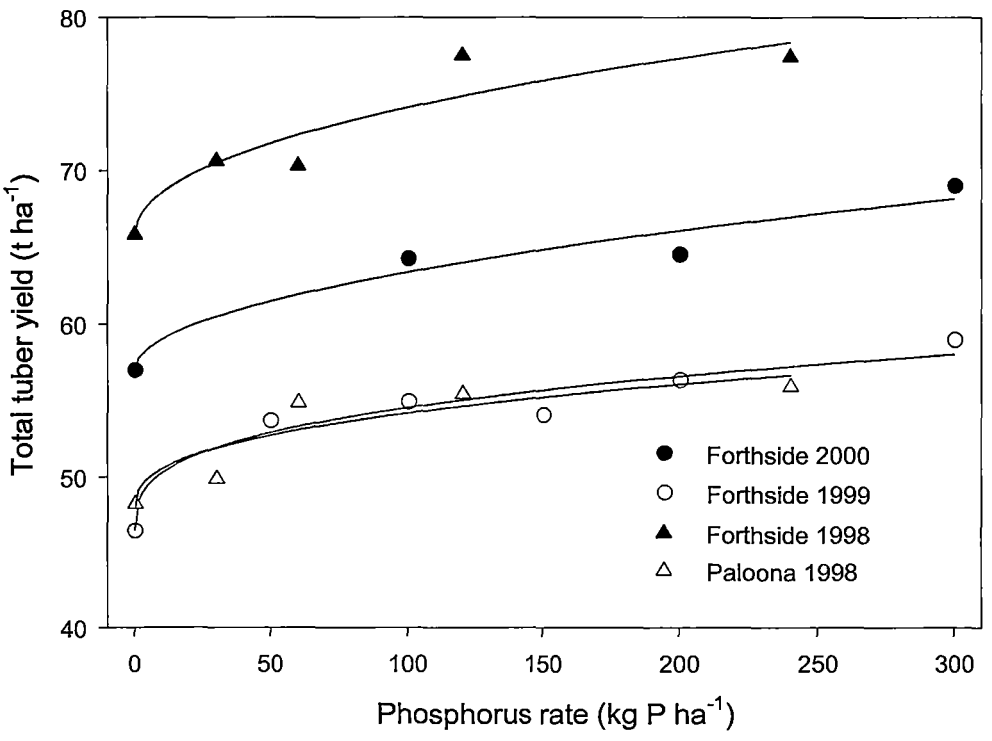


Figure 4-34. Yield responses of the four sites to applications of conventionally banded phosphorus.

There was a linear relationship of petiole P to relative tuber yield calculated for all sites (Figure 4-35). However, the petiole P concentrations were lower than those predicted by Freeman *et al.* (1998) suggesting that further yield increases may be achieved by higher petiole P concentrations. Freeman *et al.* (1998) used an average upper P rate of P 420 kg ha^{-1} compared to P 270 kg ha^{-1} in the present study. Higher P rates may be required to verify if yield increases can be obtained from higher petiole P concentrations.

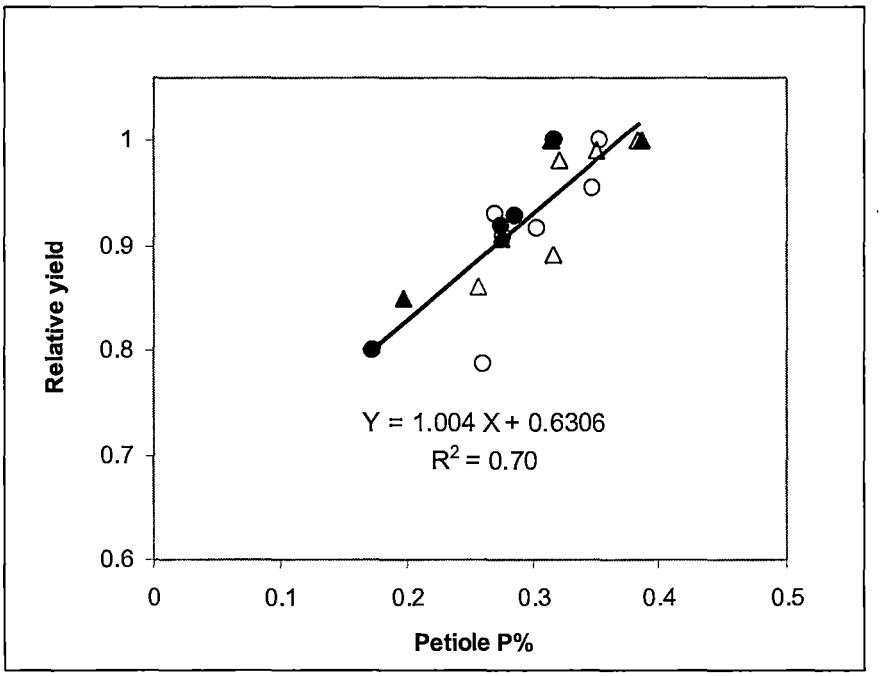


Figure 4-35. Potato tuber rela tive yield response to petiole P% at the 10-20 mm tuber stage. (●) Forthside 2000, (○) Forthside 1999, (▲) Forthside 1998, (△) Paloona 1998.

Significantly more P is applied in fertilisers than is removed in the harvested component of potato crops grown on ferrosols. The nutrient budget, expressed as the quantity of nutrient removed in the crop to the quantity of applied nutrient, in a 50-60 t ha^{-1} potato crop, ranges from 60-100% for N and K; while for P (at the recommended rates of 100-150 kg P ha^{-1}) does not exceed 20%. Within the budget the actual contribution from current season fertiliser P is between 10-20% of the total P recovered in the crop (Pursglove and Sanders, 1981). The remaining 80-90%

comes from soil P reserves. The zero P treatments from Forthside 1998 and 2000 removed 14.8 and 12.3 kg P respectively from soil reserves of P. More than 80% of the applied P remains in the soil after the crop has been removed. While there is an obvious economic inefficiency in P use, there are potentially serious concerns with associated environmental risks from such high surplus additions of P. Fortunately the movement of P in ferrosols is very limited due to the high P fixation capacity (Moody, 1994), so that the transport of P in ground water is unlikely to occur. Ferrosols contain at least 5% free iron as citrate dithionate extractable Fe (Isbell, 1996). If all of this iron is available to react with P then over 60 tonnes of P ha^{-1} can be stored in the top 10 cm of soil. Off site movement of P may occur in eroded soil (Cotching, 1995), but this issue would be better addressed by measures to prevent erosion than to limit the pool of P in potentially erodible soil.

Soils with a lower P fixation capacity, such as coastal sands and duplex profiles of the north Midlands, are being increasingly sought for potato production. These soils have a lower capacity to fix P and are a risk of off site movement of P if excessive rates of P are applied. Sparrow (1993b) demonstrated that P responses in potatoes were unlikely from P rates above 75 kg P ha^{-1}. Ten years after these results were publicised P rates in excess of 150 kg P ha^{-1} are commonly being used on these soils (Cotching unpublished). The leaching of P from sandy soils can be reduced by the application of P retaining minerals (Robertson *et al.*, 1999; Pathan *et al.*, 2000) which may be a suitable management option if a source of suitable material were available.

4.8 Discussion

Field trial of hill applied dripper irrigation and overhead sprinkler irrigation with granular starter phosphorus

Phosphorus starter treatments had no effect on petiole nutrition and a small negative effect on the canopy ground cover. This indicates there may be a reduced P efficacy from the starter treatments or an adverse effect from the close placement of P. Small decreases in the rate of emergence were observed in a preliminary trial from the spot application of starter P. There were no effects of starter treatments on tuber yield or size grades. Nitrogen was not included with the starter band in this trial. While there is often a beneficial interaction from N in the starter bands, most of the response can

be attributed to P (Bermudez and Mallarino, 2002). Laughlin (1977), when working with poppies, found beneficial nitrogen interactions occurred only when the banded P rate was above 45 kg P ha^{-1}; at lower P rates the response was due to P alone. Hence, with the starter P rate used here (25 kg P ha^{-1}) there is unlikely to be a strong N/P interaction.

Drip irrigation increased petiole P uptake from the higher P conventional band rates but did not influence the uptake of P from starter bands. The close placement of starter P in conjunction with hill soil irrigation did not affect the early or subsequent growth of potatoes on ferrosols. Even where an initial increase in petiole phosphorus content was obtained, from the conventionally banded fertilisers of the drip-irrigated crop, there was no evidence of beneficial effects in the final yield. Drip irrigation increased the ground cover of the zero P control plants and improved the acquisition of P from soil reserves. There were no significant interactions of irrigation by conventional band rate on tuber yield, but reduced soil nitrate levels may have contributed to an early senescence of the drip-irrigated crop.

Potatoes show a degree of plasticity of growth to phosphorus. Phosphorus deficient plants are slower to develop but senesce later so that differences in final yields are diminished even though favourable plant growth responses have occurred during earlier growth periods (Jenkins and Ali, 1999) and Table 4-6 p 95. Similar improvements in early vigour followed by little or no yield response from starter fertilisers have also been observed in vegetable crops (Laughlin, 1968), poppies (Laughlin 1977) and corn (Bermudez and Mallarino, 2002). However, P deficient plants require a longer growing season to achieve maximum yield. The longer growing season increases the risk of disease incidence, the likelihood of adverse harvesting conditions and reduces the time available for subsequent crops.

Significantly less water was used by the drip-irrigated crop, 310 mm, compared to 580 mm used to maintain the sprinkler-irrigated crop at the same moisture status, yet tuber yield was not affected by irrigation source. The similarity in yield was not surprising since the same soil moisture tensions (-45 kPa or less) were maintained in both treatments. Potato yields increase linearly between matric potentials of –200 kPa up to –10 kPa (Taylor and Ashcroft, 1972; Martin *et al.,* 1992). However, the

quantity of reject tubers was reduced by the drip irrigation. While this could be from the more frequent scheduling of the irrigation, a more even distribution of the water from the dripper system could also have contributed. On suitable land, both the scheduling and uniformity of irrigation can be addressed with modern sprinkler irrigators, e.g. centre pivot and lateral shift systems. However, these irrigation systems inevitably apply some irrigation water to the furrows, an effect that may be exacerbated by potato canopies (Figure 4-16 p 110), where the water may be less available to the crop.

Although no attempt has been made to cost the two irrigation systems used in this study, where costs have been calculated they often favour less efficient but lower capital cost irrigation methods. The gross margin for drip irrigation was lower than furrow irrigation of a sugar beet crop (Sharmasarkar *et al.,* 2001) and similarly in onions the gross margin from drip irrigation was lower than that from sprinkler irrigation (Al-Jamal *et al.,* 2001). Drip irrigation has a higher capital and installation cost than sprinkler systems (Shock *et al.,* 1999), and the savings in water are not likely to offset these costs at current water prices. However, with increasing prices and reduced access to irrigation water, drip systems will become more commercially attractive and have already been adopted for commercial tomato production in the Goulbourn Valley (Fisher *et al.,* 2000).

Potato canopy ground cover

Both the conventionally banded P rate and irrigation method had a marked effect on the development of the potato crop ground cover. Phosphorus rates of up to 100 kg P ha^{-1} in the conventional band significantly increased the ground cover during crop establishment while higher P rates caused only a marginal increase. There was a small negative effect of the spot starter band on ground cover, indicating a reduced availability of P from both starter band positions compared to conventionally banded P. Differences in the ground cover during senescence appear to be linked to the rate of applied P. Sparrow and Salardini (1997) observed similar increases in ground cover of P sufficient potatoes during the initial growth stages, and a longer duration of ground cover of the P deficient plants. Nitrate leaching occurred under the dripper treatments (Figure 4-4 p 88) and this may have contributed to the earlier senescence.

While ground cover can influence the yield of potatoes (Allen and Scott, 1980), other physiological and climatic factors can have more influence. The size of the tuber sink (McCollum, 1978) and respiration rates (Sale, 1973), particularly in hot dry weather, can greatly influence the bulking rate of tubers. The ground cover data obtained from the Forthside 2000 trial was useful for assessing the effects of treatments on plant growth but proved poor as a predictor of potato yield. Field measurements that account for the stress applied to plants through water deficit and transpiration (Clover *et al.*, 2001) may improve the prediction of yield from ground cover measurements. The conversion rates obtained in this study were similar to those found by Sale (1973) but are well below those found in studies in Europe (Allen and Scott, 1980; Clover *et al.*, 2001). This may indicate the crops are experiencing additional moisture or transpirational stresses.

Visual scoring and canopy image analysis during the senescence period at Forthside 1999 strongly suggested an effect of irrigation rate on canopy greenness. At the Forthside 1999 site irrigation was applied through two travelling irrigator runs. The sprinklers delivered a 50% excess irrigation between these rows. Canopy greenness was lowest in the regions of excess irrigation and highest where the irrigation rate was lower (
Figure 3-6 p 68). A similar effect was found in the Forthside 2000 trial where over watering through the drippers contributed to nitrate leaching and possible premature senescence. Soil testing revealed that nitrate had leached to below the root zone under dripper irrigated potatoes (Figure 4-4 p 88). Higher soil moisture levels used to promote P uptake run the risk of inducing N leaching if moisture is not carefully managed (Stark *et al.*, 1993). To reduce the risk of nitrate leaching split applications of N through pre plant basal application and later applications through the drippers were recommended by Shock *et al.* (1999).

Potato canopy irrigation deflection

Potato canopies affect the distribution of overhead-applied water. There may be up to a 20% deficit under the canopy and a corresponding increase in water around the perimeter of the canopy. The effect is likely to be reduced in older, post flowering plants due to the less ordered arrangement of leaves (Saffigna *et al.*, 1976).

Water deflected by the canopy and entering the furrows (Figure 4-36) may either:
a) move across laterally to the centre of the hill and then be drawn up by the lower matric potentials in the hill soil, or
b) drain down through the furrows and not contribute to the irrigation of the crop.

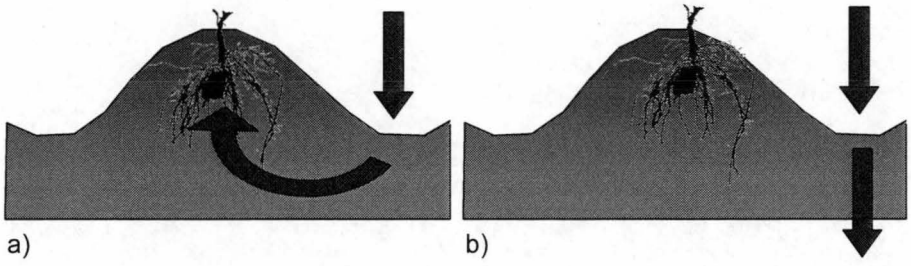


Figure 4-36. Movement of wa t er applied to potato furrows. a) Lateral and upward water flow, b) drainage through the furrows.

If the water were to move laterally, case (a), fertiliser efficiency from the conventional band may be improved by the upward flow of water through the fertiliser bands (Noborio *et al.*, 1996). The yield response to different banding positions in the first year's trial (Table 2-4 p 46) suggested this effect may prevail, but there was no comparison of irrigation method in this trial. Anecdotal evidence from the irrigation efficiency data suggests that nearly 50% of the water applied to the overhead-irrigated crop was not required by the crop (Figure 4-3 p 87). This water is most likely to have gone to deep drainage, which supports case (b). French *et al* (1973) observed that water shed to the furrows by potato crops is not detectable by a neutron probe positioned in the hill centre. Whether the water went to drainage or was utilised by roots in the furrows is not known, though Stalham and Allen (2001) demonstrated effective root growth by potatoes could occur into furrows in sandy loam soils. In this study there was only sparse root growth in the furrows; hence, water shed to the furrows was unlikely to be available to the crop.

No firm conclusions regarding soil moisture flows could be drawn from data obtained from the field trial. The moisture distribution inferred from the penetrometer data shows an initial wetting of the whole subsoil under sprinkler irrigation, followed by a decrease in moisture below the root zone. This may indicate either the uptake of water from below the root zone or the deep drainage of

the water out of the profile. More frequent and deeper sampling would help in this regard. Marker ion such as lithium (Mamolos *et al.*, 1995), chloride (Dyck *et al.*, 2003) or bromine (Ottman, 2000) could be placed in the furrows of a sprinkler irrigated crop and the distribution in the soil mapped over time to show the direction and extent of water movement from the furrows.

The deflection of water by the potato canopy may provide physiological benefits for the potato plant. The soil below the canopy would be kept drier which may help protect the tubers against rot disease and would also contribute to increased tuber respiration and hence Ca uptake of tubers (Kratzke and Palta, 1985). Nulsen (1986) observed canopy redirection in mallee plants, through stem flow, that had beneficial implications for water infiltration and subsequent plant water use. The concentration of water around the canopy perimeter would contribute to deeper infiltration from light rainfall events, which could improve water use efficiency providing root growth is not limited in the soil around the canopy perimeter.

Soil physical properties and implications for root growth

Compaction forces of around 150-400 kPa may be applied to the soil surface during typical planting operations (Koolen and Kuipers, 1983). These forces alone are not sufficient to cause a restriction of root growth. However, given the strong influence of soil moisture content on a soil's susceptibility to compaction, soils that are compacted when wet may reach bulk densities sufficient to limit root growth. There are indications that the depletion of water menisci between aggregates when a soil dries leads to a reduction of the penetration resistance of low bulk density soils (BD<1.05 Mg m^{-3}). Such reductions in penetration resistance do not take place in soils of higher bulk densities (BD>1.05 Mg m^{-3}) which continue to increase in strength as the soil dries. The well cultivated soils typical of potato hills are unlikely reach soil strengths capable of inhibiting root exploration at any stage of dryness; whereas the compacted furrow soil and subsoil may readily attain strengths sufficiently high to cause root growth reduction. The effects of compaction on saturated hydraulic conductivity were explained adequately by BD alone. Saturated hydraulic conductivity is unlikely to be limiting the water supply to potato crops under field conditions.

Soil physical properties and implications for root growth

There appears to be very little effect of the initial soil moisture on the soil properties measured after compaction other than that on the bulk density itself. This was an unexpected result given the different modes of aggregate failure with changes in soil moisture conditions (Gupta *et al.*, 1989; Tamari, 1994) . More shattering and greater water holding properties might have been expected from a compacted dry soil than the same soil when compacted wet. The important feature is that a soil's ability to resist a given compacting force is greatly reduced by an increase in soil moisture. This is evident in Figure 4-19 p 115 where doubling the moisture content from 10% to 20% results in a four fold decrease in penetration resistance of the 1.3 Mg m^{-3} BD soil, hence the soil's ability to support a load is greatly reduced. After the application of equivalent compaction loads the bulk density of a moist soil will far exceed that of a dry soil.

The difference in penetration resistance between soils of BD of 1.05 and 1.1 Mg m^{-3} at gravimetric water contents below about 20% may represent the boundary between aggregated and massive behaviour of the soil. That is, the macro aggregates of an aggregated soil at these water contents are held together predominantly by water menisci linking the surface of aggregates; whereas in a massive soil it is the pores within, and on, shared surfaces between squashed aggregates that hold the soil together (Figure 4-37) (Taylor and Ashcroft, 1972).

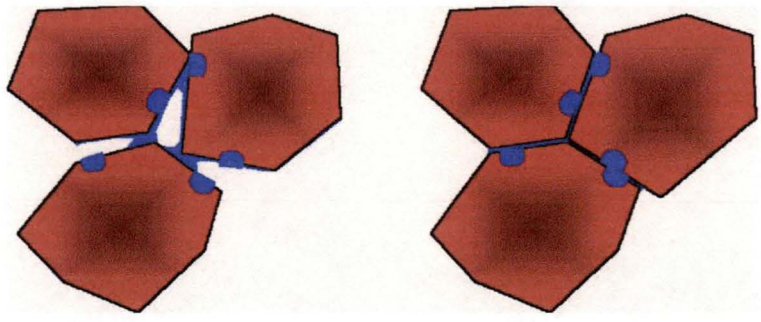


Figure 4-37. Effect of compaction on inter-aggregate alignment and water menisci. Left: only menisci at the contact points of aggregates contribute to the strength of uncompacted soil. Right: in compacted soil aggregates are held together by pores along the entire contact surface of aggregates.

This difference is primarily brought about by the amount of deformation at the contact point of aggregates (Gupta *et al.,* 1989). Failure at the point of contact between aggregates results in an enlargement of the contact surface and the sharing of fine pore spaces along the boundary of the aggregates. Pores within aggregates are usually in the size range of 10-0.1 μm with corresponding matric tensions of 30-3000 kPa (Hamblin, 1987). Hence, the pores formed between the contact of adjacent aggregates are able to provide resistance to the separation of aggregates, through the development of suction forces equivalent to three MPa and higher. The proportion of this force expressed by the soil depends on the relative contact area between aggregates. In a massive soil the whole surface area of what were the aggregates are in contact and the associated strength is at a maximum. The contact component reaches a minimum in a freely aggregated soil.

In well-aggregated soil, only water menisci associated with the thin water films surrounding aggregates contribute to soil strength. The water pores associated with surface menisci are larger (10-1000 μm) and are broken by lower forces, typically less than one MPa (Figure 4-20 p 116). Hence for a soil with free aggregate behaviour (BD<1.05 Mg m^{-3}) soil strength will increase while the soil dries until a critical point is reached at which the surface menisci between aggregates break or are greatly diminished, and soil strength begins to decrease again.

Potato root growth is inhibited by penetration strengths of more than 2Mpa (Bishop and Grimes, 1978). The transition between aggregated and massive soil behaviour at a bulk densities of 1.05-1.10 Mg m^{-3}, and the associated increase in penetration resistance as the soil dries, could be used to indicate the soil conditions in which potato root growth can no longer occur. The absence of interactions between the initial moisture content at compaction and saturated hydraulic conductivity and penetration resistance properties allows bulk density to be used to interpret soil conditions suitable for root growth.

Potato root growth in glasshouse trials

Only limited root growth occurred into the dry compacted subsoil of the experiment comparing soil moisture and mild sub soil compaction (Figure 4-25 p 123, Figure 4-26 p 124). Yet, there was adequate root growth into the other soil treatments. Soil

strength was the main limiting factor since the loose dry topsoil did not greatly inhibit root growth. The results from the matric potential experiment (Figure 4-24 p 121) indicate that very dry conditions, much drier than would usually occur in a potato crop, are required before root growth ceases due to desiccation alone. Soil strength was found to be the main limiting factor on potato root growth.

The roots of unhilled potato plants grow beyond the radius of the canopy drip line and would therefore be able to utilise water shed through canopy deflection. The hilling of potato crops confines the natural pattern of root growth (by reducing high root densities in the furrow soil) which may have implications for water and nutrient use efficiency.

Potato root growth in field trials

The root distribution of field grown potatoes was strongly influenced by soil conditions. There was an indication that higher soil moisture levels directly below the hill may be promoting deeper rooting in the drip irrigated crop (Figure 4-30 p 129) similar to observations by Rab and Willatt (1987) and Parker *et al.* (1989) that improved soil moisture encouraged deeper rooting. This is contrary to findings by Stalham and Allen (2001) that irrigation promoted surface rooting while droughted plants were able to grow roots down to 100cm. The soil used in the study by Stalham and Allen (2001) was sandy and showed no indication of compaction induced root-limiting conditions at depth.

The furrow soil remained moist throughout the growing season, yet there was very little root growth into the furrows. Moistening the soil is not sufficient to promote root growth. The high penetration resistances occurring in the furrow soil (>3 MPa) on the occasions when it does dry are likely to inhibit root growth into the furrows. Measurements of soil volumetric water content and matric potential in both the sprinkler and drip irrigated treatments showed greater fluctuations of moisture in the hill soil (0-400 mm), than in the deeper soil layers of the hill or in the furrows. This is likely to be a direct consequence of the high root density in the hill soil and hence greater water extraction from this zone. Although the soil in the hill has the highest root density, which is an advantage for phosphorus uptake (Barber, 1982), the rapid

drying of soil associated with such high root density may not be favourable to P diffusion and uptake (Stalham and Allen 2001).

A lower moisture content in the subsoil may also be restricting root growth into the subsoil of the sprinkler irrigated crop. Deeper rooting depths were observed under the drip-irrigated crop, which is attributed to the higher moisture content and subsequent lower soil strength. Higher moisture contents in the subsoil, however, increase the risk of nitrate leaching. Nitrogen management would need to be addressed should drip irrigation be commercially used (Shock *et al.,* 1999).

5 Conclusions

There was no conclusive evidence that starter P bands improved the utilisation of fertiliser P by potatoes grown on Tasmanian ferrosols. Granular starter P applied at Forthside and Paloona during the 1998 season had an effect on petiole nutrition. However, this response was only about half that which could be attributed to an equivalent amount of conventional band placed P (Table 2-6 p 47). There was no effect of starter placed P on the final tuber yield. The liquid starter P from the second year's trial, in 1999, had no effect at all under field conditions, though perhaps by using higher concentrations of P a response may have been obtained. Responses were found, however, to higher concentrations of liquid P in pot trials (Table 3-7 p 73). Starter fertiliser responses to higher strength liquid solutions cannot be ruled out.

Confining irrigation to the hilled soil, through dripper irrigation in the final trial at Forthside in 2000, produced no responses to starter placed P. Drip irrigation increased the petiole P concentrations of higher conventional band P rate treatments compared to those with sprinkler irrigation. Further petiole sampling would have confirmed if the response was due to initial differences in soil water contents from the two irrigation methods, or from a prolonged effect of drippers increasing the availability of conventional band placed P. There were no associated effects of drip irrigation on tuber yield or size, though the quantity of reject tubers was reduced by drip irrigation. Increasing the P nutrition during the early growth stages does not appear to influence final yield, a result also found by Jenkins and Ali (1999). Higher

P nutrition can reduce the length of time for the crop to reach maturity (Jenkins and Ali, 1999). The reduction in ground cover duration of the drip-irrigated crop may have resulted from higher P nutrition. However, nitrogen leaching occurring under the drip-irrigated crop may also have caused premature senescence (Figure 4-4 p 88).

In comparison to other crops, the seed piece of potatoes contains large reserves of nutrients and water (Klobe and Stephan-Beckmann, 1997). A 50 g seed piece contains 170 mg of P which if it is all translocated can account for the P requirement of a 26 day old plant. This enables potatoes to establish a substantial root system and stem growth in nutrient poor conditions, (Figure 3-7 p 71) and under droughted conditions (Figure 4-24 p 121). Adequate moisture and nutrition may accelerate the emergence and development of potatoes, but is not essential for establishment (Moorby, 1968). However, small seeded crops may fail to establish if a ready source of nutrition and moisture is not at hand (Laughlin, 1968; Costigan, 1984). Starter fertilisers applied to a range of crops, not including potatoes, were placed either with the seed or within a 50mm radius beside and below the seed in combination with broadcast fertilisers (Bednarz *et al.*, 2000; Bullock *et al.*, 1993; Gordon *et al.*, 1998; Guthrie, 1991; Hutchinson and Howard, 1997; Rhoads and Wright, 1998; Stecker *et al.*, 2001; Stewart and Edmisten, 1998; Stone, 1998; Swiader and Shoemaker, 1998). Conventionally banded fertilisers applied to potato crops in Tasmania are placed within the radius of 50 mm below and 50 mm beside the sett in two bands (Regal, 1988). Potato roots were found to reach the conventionally placed fertilisers by the time shoots were emerging at the soil surface (Figure 2-4 p 49). The conventionally placed fertiliser bands are likely to be sufficiently close to satisfy the early P requirements of the crop. Compensatory growth of P deficient plants may limit the yield benefits from improved early P nutrition as has been reported in potatoes (Jenkins and Ali, 1999) and corn (Bullock *et al.*, 1993).

Field data and results from a computer model have shown that up to 20% of the water falling onto the canopies of potato crops can be shed by the canopy into the furrows. The resulting lower water infiltration into the hill soil was initially proposed as a mechanism for the reduced availability of granular starter placed fertilisers (Section 2.3 p 51). It is evident from the drip irrigation results, where irrigation was confined to the hill soil, that factors other than a lower absolute supply

of moisture in the hills may be affecting the uptake of starter band fertilisers. However, drip irrigation did improve the early uptake of conventionally banded P and the ground cover of young plants compared with control (zero P) applications. This finding indicates that increases in soil moisture can improve P uptake. Simpson (1962) showed P uptake of potatoes was increased more by increased irrigation than by P applications of 60 kg ha^{-1}, and Baerug and Steenberg (1971) demonstrated improved P uptake of potatoes due to wetter irrigation regimes. Managing irrigation may be a means of further improving P efficiency on potatoes.

A reservoir of moisture maintained below the conventional band, through a low root density in this region (Figure 5-1), could facilitate P uptake of the sprinkler irrigated crop (Baerug and Steenberg, 1971; Holliday and Draycott, 1968). Deeper placement of P, to take advantage of moisture at greater depth, has proved beneficial when rainfall or irrigation is limited (Holliday and Draycott, 1968). Deep placement, however, increases the risk of an initial P deficiency due to the greater length of time between emergence and the interception of fertiliser (Costigan, 1987). Unfavourable soil conditions, such as a higher soil bulk density, may also reduce root growth at greater soil depth.

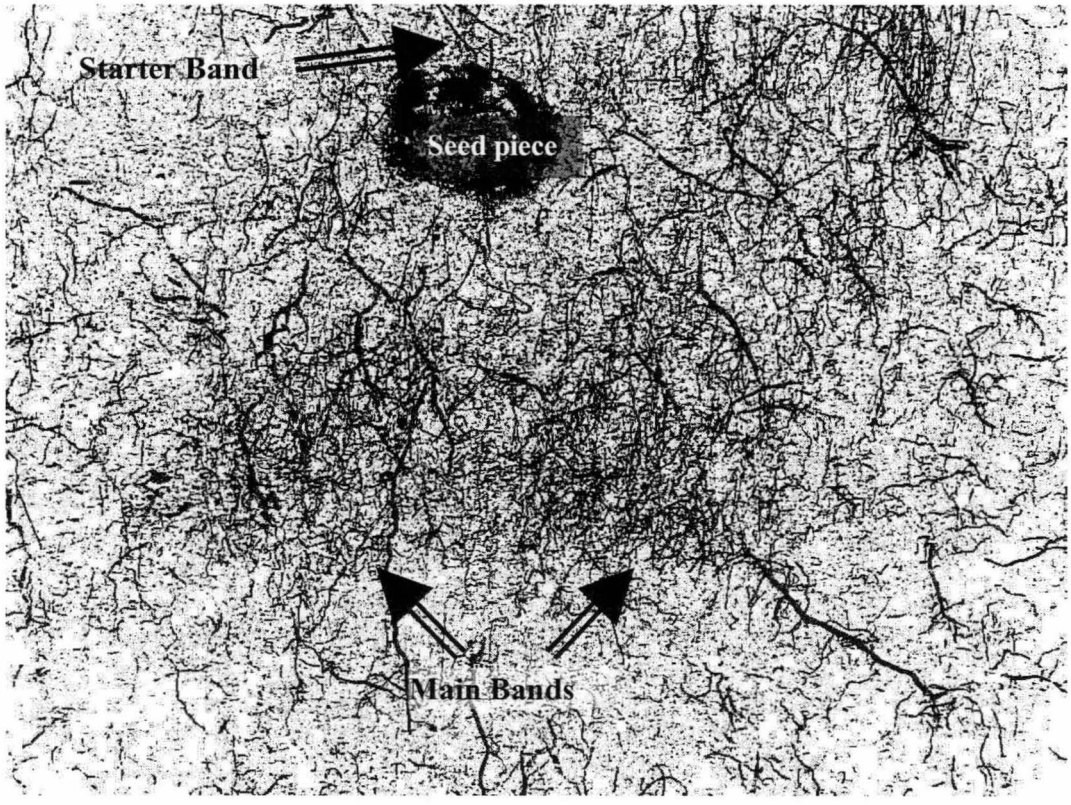


Figure 5-1. Formation of highly branched roots in the conventionally banded fertiliser position: sett is centre top of picture, conventionally banded fertiliser is placed below and to the side of the seed, centre of image. Image from Forthside 2000 trial.

Root to soil contact can be reduced in soils of low bulk density (Pietola and Smucker, 1998). Roots can readily penetrate the hilled soil but may have trouble establishing contact with the soil and the subsequent extraction of nutrients. The development of tubers in and around the starter band may further disrupt root activity in the starter band region. Robertson *et al.* (1954) attributed a reduced accessibility of P banded in the furrow of corn plants, compared to P banded 50 mm below and 50 mm beside the seed, to unfavourable moisture conditions and a lack of absorbing roots in this zone. The utilisation of P by potatoes from the starter band may decrease after roots are damaged or dislodged from the soil by compression and soil movement associated with tuber growth. While there was no direct evidence of tuber growth affecting root activity, there was ample evidence of root proliferation in the conventional band position (Figure 5-1) but no observations of such proliferation in the starter position.

Potato crops offer a unique combination of circumstances including the deflection of irrigation water by the canopy, field drainage patterns through hilling, and soil compaction in the furrows. These all contribute to and affect the water distribution and soil zones suitable for root growth, which influence the subsequent utilisation of fertilisers. The shedding of irrigation water to the furrows is of concern for water and fertiliser efficiency, particularly where root density in the furrows is low.

Any methods to improve root growth, particularly into the furrow soil, should be investigated. Effective ripping of the furrows may help improve root growth into the furrows and water use efficiency. Wide beds (Robinson, 1999) allow the water to lie on a flat surface and may improve infiltration. Root growth would not be restricted between crop rows within a bed, which would help to improve the utilisation of water shed from the canopy.

Appendix I

During the preparation of the soil solution extracts (Section 3.1.1.1 p 54) the addition of Lanthanum to precipitate dispersed Al and Fe as suggested by Moody (1995) was omitted. This appendix explains a correction based on the relative abundances of Al, Fe and Mn.

Aluminium and iron occur in specific ratios in the clay minerals of ferrosols with around 14% Al and between 6-15 % Fe (Graley and Loveday, 1961; Stace *et al.*, 1972); hence quite small quantities of suspended soil in the soil solution extracts will result in a large increase in the Al concentration. Mn on the other hand is only a minor component of ferrosols (Tiller, 1959) and hence suspended soil contamination will only marginally increase the Mn concentration. Mn is most common in the sand sized fraction, (Tiller, 1959), where it forms ferromanganiferous nodules (Isbell, 1996). Since sand size fraction is less likely to suspend in solution, suspended Mn would be expected in only very low concentrations in the soil solution. Hence the ratio of Fe to Al may be used to indicate the presence of suspended soil particles in the soil solution extract. The molar ratio of Fe:Al in ferrosols ranges between 0.2-0.54 (Graley and Loveday, 1961; Stace *et al.*, 1972).

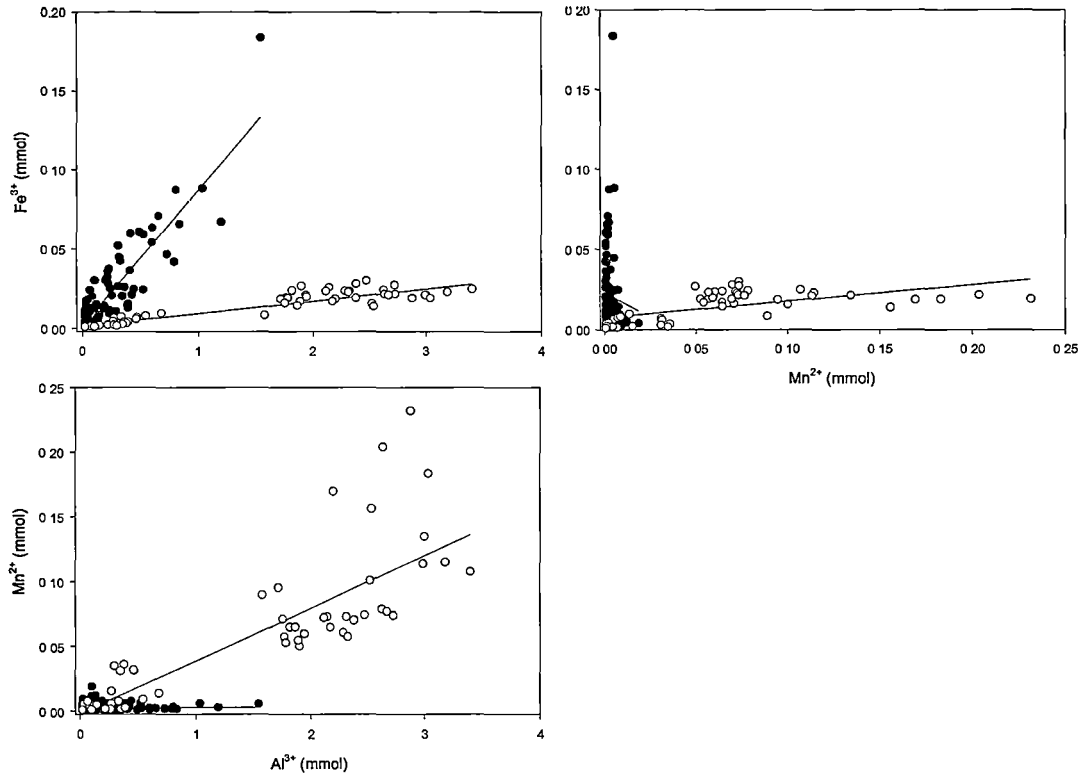


Figure AI-0-1. Total soil soluti o n extract ratios of Fe:Al, top left, Fe:Mn top right and Mn:Al bottom grouped according to occurrence in mineral pool Fe:Al ratio > 0.025 (●), or solution pool Fe:Al ratio < 0.025 (O).

Two pools of the cations Al, Fe and Mn were identified by paired comparisons of their concentration in the soil solution extracts. An empirical Fe:Al ratio of 0.025 was chosen to segregate the mineral and solution pools of Fe and Al. These pools are a mineral pool, due to suspended soil particles, and a solution pool controlled by the dissolution of Al^{3+} and Mn^{2+}, but only moderate amounts of Fe^{3+}, at low pH. These two pools can be readily seen in (Figure AI-0-1). The mineral pool had a relatively low Fe:Al ratio (0.085) which is lower than the ratio of Fe:Al in soil minerals of (0.2-0.54) (Graley and Loveday, 1961; Stace *et al.*, 1972). Hence the readily suspended mineral pool may have a composition that is different from the bulk mineral pool. The solution pool has a Fe:Al ratio that was less than one thenth of the mineral pool ratio. Total soil solution Fe^{3+} was highly correlated with both mineral and solution Al^{3+}, but at different ratios of Fe:Al (Table AI-1); while total Mn was moderately correlated with solution Al^{3+} and only weakly correlated with solution and mineral Fe^{3+}. Mn^{2+} was independent of mineral Al^{3+}.

Table AI-1. Correlation between Al, Fe and Mn in mineral and solution forms.

Mineral ratio	Form	R^2	Slope
Fe:Al	mineral	0.80	0.085
	solution	0.82	7.60E-03
Mn:Al	mineral	0.00	1.39E-04
	solution	0.65	0.041
Mn:Fe	mineral	0.31	0.027
	solution	0.37	0.103

The activity of Al^{3+} and Mn^{2+} are increased by a decrease in soil pH. However, the poorer correlation between Al and Mn compared to the Al to Fe ratio (Table AI-1) supports evidence that Al and Mn originate from independent acid solubalised pools. This can be shown by manipulating the redox potential to affect Mn^{2+} solubility without affecting Al^{3+} (Sparrow, 1985). The corrections based on the Fe to Al ratios appear to be valid. However, it would have been better to use Lanthanum chloride to remove suspended soil particles from the solution.

Appendix II

Spatial distribution of available P and K at the Forthside 1999 and 2000 trial site

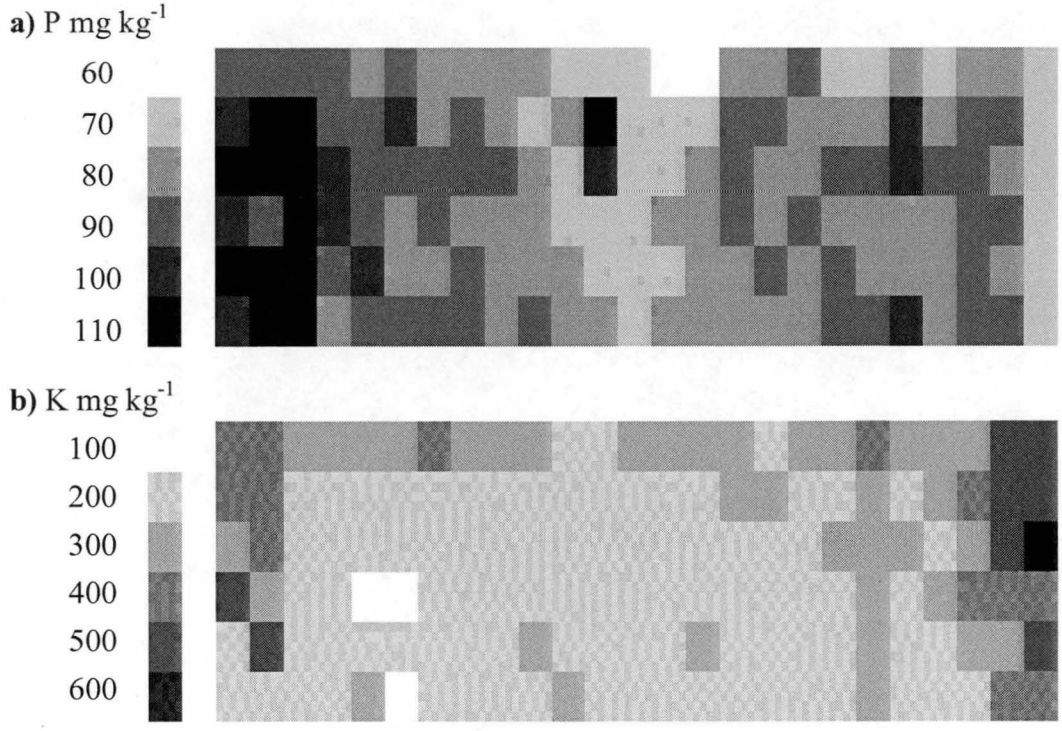


Figure AII-0-1. Spatial distrib u tion in a) soil Colwell P and b) soil Colwell K at Forthside 1999.

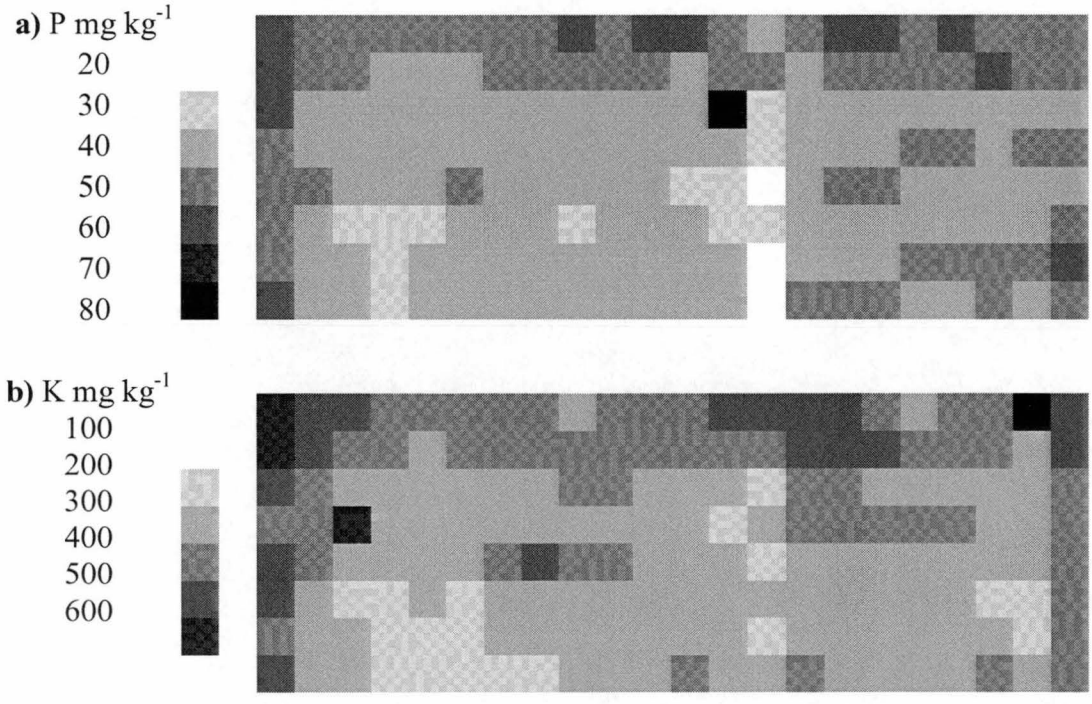


Figure AII-0-2. Spatial distribution in a) soil Colwell P and b) soil Colwell K at Forthside 2000.

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